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SUMMARY FINAL REPORT

ALS
ENGINE PROPELLANT EFFECTOR SYSTEM

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

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The Requirement For Use Of International System Of Units Has Been Waived For This Document

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ALS
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Contract NAS8-38073

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1.0 INTRODUCTION

This is the Final Summary Report for the Advanced Launch System (ALS) Propellant Control Effector System, Contract NAS8-38073. This program was conducted by Aerojet Propulsion Division (APD) for NASA's Marshall Space Flight Center (MSFC). Authority-to-proceed (ATP) was given on 30 May 1989. APD was directed to close out the program on 6 August 1993.

The objective of the program was to evaluate highly reliable, low cost propellant control effector (valve plus electromechanical actuator) systems for the ALS engine. The total effort planned is defined in DR-15, Technical Implementation Plan. Due to funding constraints, particularly in later stages of the program, and due to premature close-out, the program was not completed as originally planned. However, significant data from design and component tests were obtained. Residual hardware could also be applicable to future NASA programs.

Funding was limited for program closeout. APD was therefore directed to minimize the final reporting effort. This document does not have the depth normally associated with program final reports but, accepting the limited effort permitted, is designed to enable readers to understand the program scope and content, and to lead them to reference material which gives more detailed program data. It gives a top level overview of the program, highlighting results and data pertinent to likely future NASA programs. Recommendations are made for follow-on work which could be performed using data and/or hardware available from this program.

The program as planned consisted of two distinct phases:

Phase 1:

- Perform trade studies and analyses to provide a preliminary design of a highly reliable, low cost electromechanically actuated valve
- Conduct experimental testing to demonstrate technologies to be used in the design
- Develop a preliminary cost model to define recurring costs

Phase 2:

- Prepare a detailed design of the effector system
- Fabricate two systems and demonstrate feasibility of design through testing at MSFC
- Complete a detailed cost model

Figure 1-1 shows the overall program logic and the interrelationships between tasks. The two phases were originally scheduled to be performed over a 38 month period: 17 months for Phase I and 18 months for Phase II. The program master schedule is presented in Figure 1-2.

The report is structured around the program work breakdown structure (WBS) shown in Figure 1-3. By reporting in this fashion, the reader is informed on the total program plan content as planned, and on actual results achieved in each specific WBS task prior to program closeout .

2.0 KEY ACCOMPLISHMENTS

2. 1 Overview

This program generated and/or utilized a number of innovative approaches to the design, manufacture, and test of LO_2/LH_2 propellant effectors. The program focused on the production and demonstration of a reliable, low cost, fault-tolerant effector design for cryogenic propellant flow control. An experimental effort was conducted early in the program to verify key technologies and to characterize commercial technology being incorporated in the design. The experimental test hardware has been delivered to MSFC and is thus available for further testing or for integration with future valve/electromechanical actuator (EMA) development activities. A detailed design of the EMA was also completed. As a result of budget constraints, fabrication of this design was not initiated.

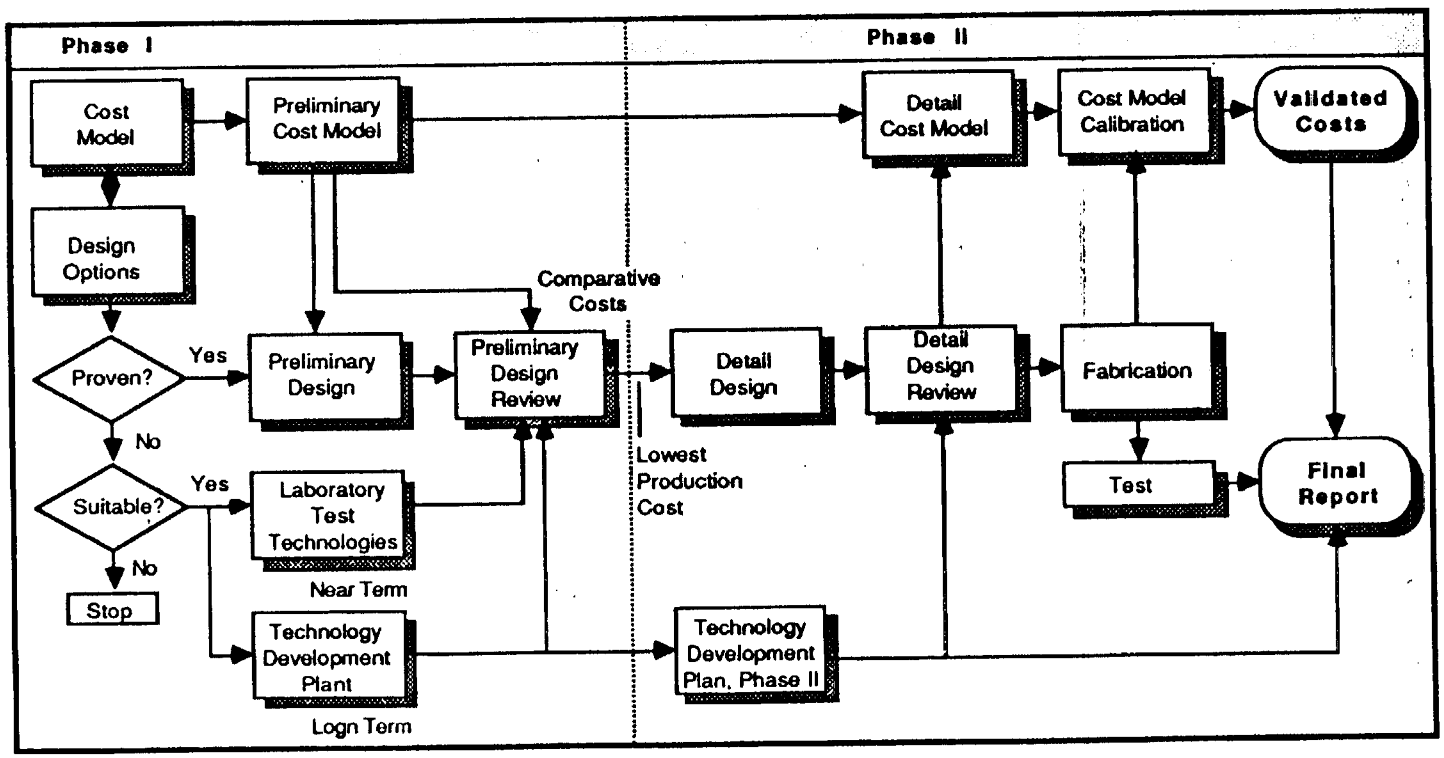


Figure 1-1. Master Program Logic

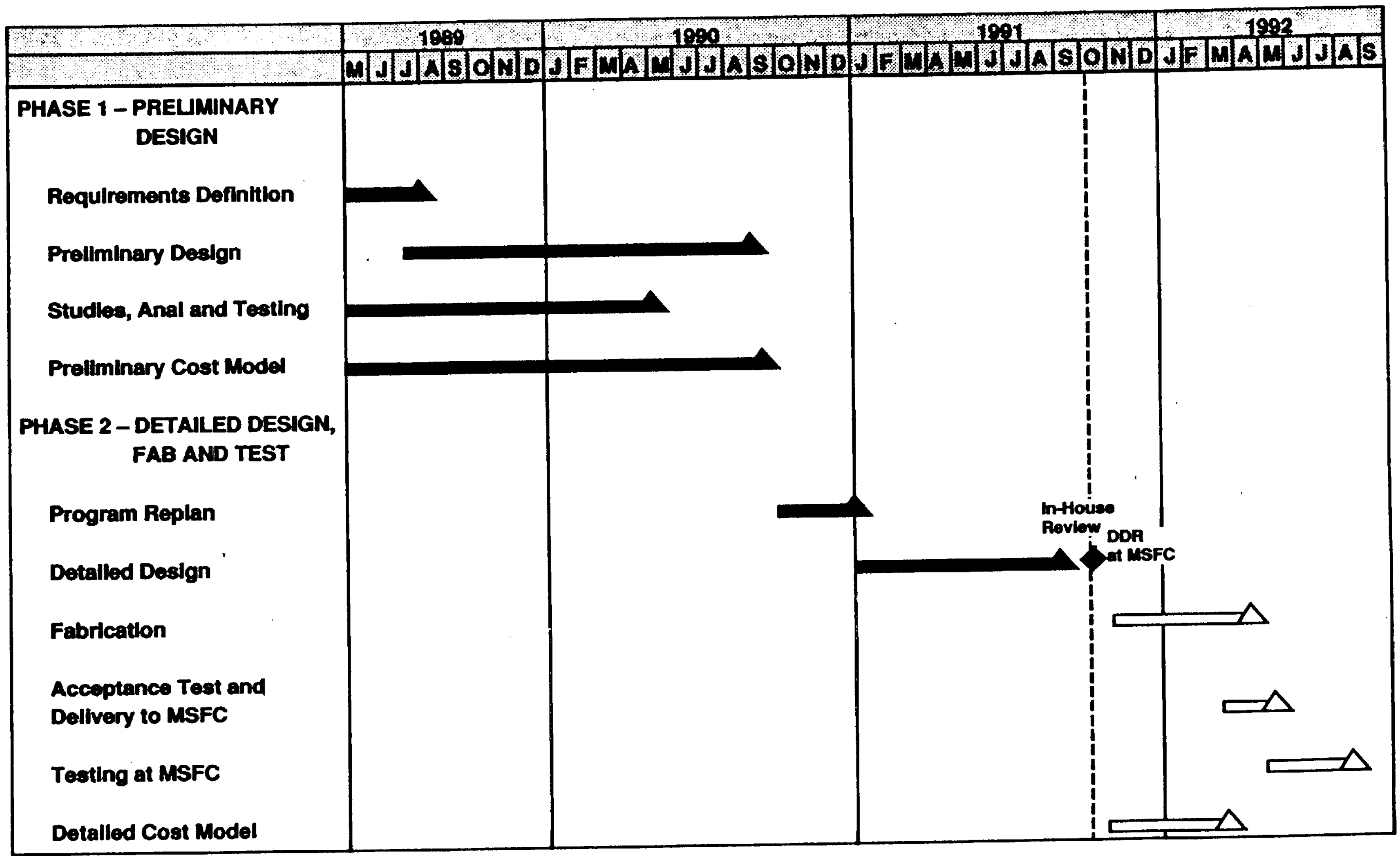


Figure 1-2. Master Program Schedule

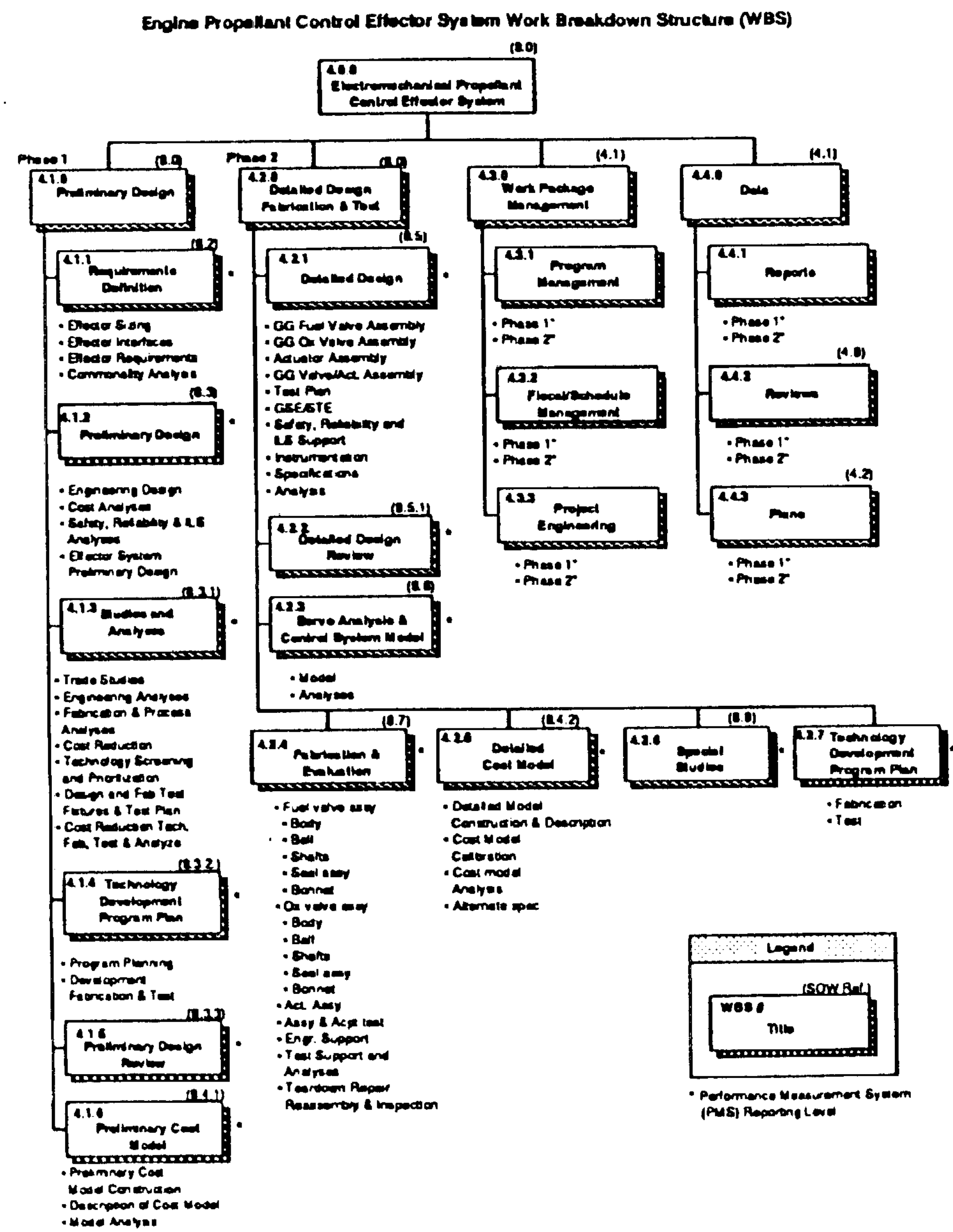


Figure 1-3. Work Breakdown Structure

2.2 Valve Design

Preliminary designs of effector valves for gas generator propellant control and for main chamber propellant control were completed. Details, including drawings, are contained in the Propellant Control Effector Preliminary Design Review (PDR) package.

Numerous trade studies were conducted in support of the valve design effort. Primary studies included:

- Floating vs. trunnion-mounted ball
- Eccentric vs. concentric ball
- Flanged vs. flangeless connections

Final selection was a trunnion-mounted concentric ball valve with weld stubs for direct welding to propellant ducts.

An experimental program was conducted to provide supportive data for the gas generator valve preliminary design effort. Tests were performed using a valve test fixture which approximated gas generator valve internal geometry. The test sequence consisted of breakaway and moving friction torque tests followed by a series of life cycle tests and dynamic flow torque tests. Friction torque tests demonstrated a consistent data trend showing slightly elevated breakaway torque followed by relatively flat running torque. Life cycle tests verified that no significant wear occurred during the 1000 cycle life required. Dynamic torque curves demonstrated good linearity for various valve openings. Pressure and flow rate measurements made during the experiments were used to characterize valve admittance coefficient, Kw, as a function of valve position. Hardware used during this test series has been shipped to MSFC.

Due to budget constraints, no further design or experimental work was performed on any of the valve configurations.

2.3 Electromechanical Actuator

A detailed design of the EMA was completed. This was configured as a common design which could be used for both gas generator and main propellant valve control. Details, including drawings, are contained in the Detailed Design Review package.

Significant trade studies were conducted to define the basic EMA assembly configuration. These trades included:

- Motor selection (AC vs. DC brushless)
- Analog vs. digital control
- Command interface
- Separately vs. integrally mounted electronics
- Gear reducer selection
- Encoder vs. resolver position sensing

These trades resulted in a modular EMA with redundant, integrally mounted digital control electronics and brushless DC motors, harmonic gear reduction, resolver position sensing, and MIL-STD-1553B digital command interface.

Numerous experiments were conducted early in the design process to support trade studies and to verify design selection. A brushless DC motor assembly and motor load fixture were built to evaluate speed/torque characteristics and to characterize the torque load imposed by a failure in one of the redundant motors. Tests results demonstrated close correlation with analytical estimates.

A harmonic gear reducer was built and tested at the Harmonic Drive Company facility in Massachusetts to demonstrate torque, torsional stiffness, and backlash characteristics. This same unit was also tested in a cold box to measure gear reducer efficiency as a function of temperature. The unit exhibited a 30-40%

drop in efficiency in the cryogenic region. A valve test fixture was fabricated and used in conjunction with the gear reducer to characterize the thermal gradient across the reducer. Tests were performed at an interface temperature of -300°F.

The motor and gear reducer were combined with motor drive and digital control electronics to characterize the performance of a single string digital control system. A load test fixture was designed and fabricated. Tests were conducted over a load range of zero to 900 inch-pounds. Parameters evaluated included step response, frequency response, slew rate, position accuracy, holding torque, and duty cycle characteristics. A prototype version of this digital control system was fabricated and delivered to the MSFC Electronics Laboratory for further evaluation.

Tests were also performed on EMA electronics. A breadboard version of the motor driver circuit board was fabricated and evaluated with the brushless motor assembly. The circuit was tested for proper motor phasing, overcurrent protection, velocity feedback control, and forward and reverse operation. Speed versus input voltage for the circuit was also characterized. Additional tests also demonstrated the resolver-to-digital converter interface. Tests were conducted with a commercial 80C196 evaluation board.

A significant portion of the operational firmware code was also generated and evaluated during component and system testing. Specific items coded and tested included:

- Closed-loop position control (proportional plus derivative)
- Resolver-to-digital conversion including reference signal generator

All hardware used during EMA testing has been shipped to MSFC and could be used to support future EMA programs.

Due to budget constraints no detailed design hardware was fabricated or demonstrated.

2.4 Cost Model

A preliminary cost model was developed which was used to track program progress in meeting design-to-cost goals. This is a comprehensive data base addressing recurring in-house manufactured ("make") and supplier-provided ("buy") parts and recurring operations and support (O&S) costs. The cost model is Microsoft Excel application-based and can be used on either Macintosh or PC desktop computers. The model has applicability to any engine component and will consolidate costs up to the engine level. It gives the model user authority over input costs and manufacturing cost relationships. The model has not been validated but is a potentially useful tool for unit production cost projection and tracking.

3.0 TASK SUMMARIES

3.1 Requirements Definition

3.1.1 Objective

The objectives of this task were to: conduct analyses to size the propellant control system and identify all interfaces; define requirements and sizing for the valve, valve actuator, and drive electronics; define reliability allocations, based on engine-level considerations, and leakage requirements.

3.1.2 Activity Overview

This task consisted of several subtasks, as follows:

Effector Requirements

Effector requirements were developed from engine-level operational and environmental considerations, as summarized by Figures 3-1, 3-2, and 3-3.

PARAMETER	MOV	MFV	GGFV	GGOV	REMARKS
FLOW MEDIA	LOX	LH^2	LH^2	LOX	
FLOW RATE (lbs/sec)	1119 ± 10	189.0± 2.0	26.2 ±1.5	20.6 ± 2.6	
INLET PRESSURE (psi)	2948 ±164	3586 ±375	3586 ±375	2948 ±164	
OPERATING TEMP., °R	176.0 ± 2.0	81.0 ± 2.0	300.0 ± 20	176.0 ± 2.0	
PRESSURE DROP (psid)	21 ± 5	10 ±5	55 ±10	3 ± 1 *	Pressure drops are lower than those supplied by MSFC
LEAKAGE (Internal closure, scc/min)	30	30	7	7	
LEAKAGE, External Dynamic shaft seals, (scc/min) Static seals, (scc/sec)	30 $7x10^{-4}$	30 $7x10^{-4}$	7 $2x10^{-4}$	7 $2x10^{-4}$	Leakage rates are with Helium at 50 psid. Leakage wont significantly change during cycle life required.
MINIMUM CYCLE LIFE	700/300	700/300	700/300	700/300	700 dry checkout/300 operational
THROTTLING RANGE			60 - 100%	60 - 100%	
RELIABILITY ALLOCATION	0.9998	0.9998	0.9998	0.9998	
ENVIRONMENTS VIBRATION (G'S RMS) TEMPERATURE PRESSURE HUMIDITY SALT FOG	X - AXIS 38.51 16.94 22.58	Y - AXIS 12.76 22.42 26.93	Z - AXIS 21.7 16.18 22.49		See valve requirements document with handout. Total Composite Level Zone M Zone M-1
FACTORS OF SAFETY YIELD FACTOR ULTIMATE FACTOR	1.10XLIMIT 2.0XLIMIT	1.10XLIMIT 2.0XLIMIT	1.10XLIMIT 2.0XLIMIT	1.10XLIMIT 2.0XLIMIT	
CLEANLINESS	ATC-STD 4940	ATC-STD 4940	ATC-STD 4940	ATC-STD 4940	Clean all valves to ox clean level for commonality.
INTERFACE	weld stubs	weld stubs	Nallex seal, bolt flange	Nallex seal, bolt flange	Nallex seal is a dual vearited seal

* GGOV pressure drop is too low for good control. Design will be changed to increase pressure drop and will be discussed in trade studies and commonality analysis.

Figure 3-1. Valve Requirements Summary

Type	Electromechanical - Rotary
Force (lb-in)	*Main Valve - 600 GG Valve - 250
Rate (deg/sec)	*Main Valve - 135 GG Valve - 180
Acceleration (deg/sec)	Main Valve - 2250
Duty Cycle	90° CW + 10 min. Holding + 90° CCW
Life	300 Cycles @ Rated Torque + 700 Cycles @ 25% Rated Torque
Position Accuracy	*± 1 degree
Backlash	0.5 degree
Spring Rate	2500 lb/degree
Power	28 ± 4 volts DC
EMC	*MIL-STD-461C Catagory A2a
Electrical Connector	MIL-C38999
Redundancy	*Two Independent Electrical Channels
EEE Parts	MIL-STD-975 Grade 2

* Cost Drivers

Figure 3-2. Actuator Requirements

Temperature	Operational Ambient - 50°F To + 130°F	
	Valve Interface -320°F	
	Storage - 65°F To + 130°F	
Pressure	15.23 psia To 10^{-6} Psia	
Humidity	8% To 100% Relative Humidity	
Salt Fog	1% Salt Solution 30 Days	
Sand And Dirt	140 Mesh Silica, 0.25 gm/ft^3, 500 ft/min	
Vibration	X axis	38.51 g rms
	Y axis	12.76 g rms
	Z axis	21.7 g rms

Figure 3-3. Environmental Requirements

Effector Sizing

The valves were sized to meet the engine pressure schedule requirements. This resulted in the main propellant valves having a 5 inch line diameter and a 4 inch ball hole diameter. The gas generator valves were sized at 1 inch. Oxygen flow is so low that the pressure drop through this valve is insufficient for acceptable control authority. Two options were evaluated during trade studies: use of a smaller valve of the same design, or use of the same valve as the hydrogen circuit gas generator valve with an underbored ball. The latter option provided an alternate way of achieving the fuel lead requirement. The trade study led to the selection of a reduced bore valve.

Valve Interfaces

Valve interfaces were coordinated with the STME program. The conclusion, scheduled for further evaluation during the fab studies, was that the main propellant valves would be part of welded manifold subassemblies. The gas generator valves would be flanged into the lines, probably by clamping with through-bolts between two mating flanges. The seals chosen were Naflex seals; these provide double sealing and can be vented if required. Figures 3-4 and 3-5 show the selected approaches for the main valves and gas generator valves, respectively. The interface between the actuator and the various valves is shown in Figure 3-6.

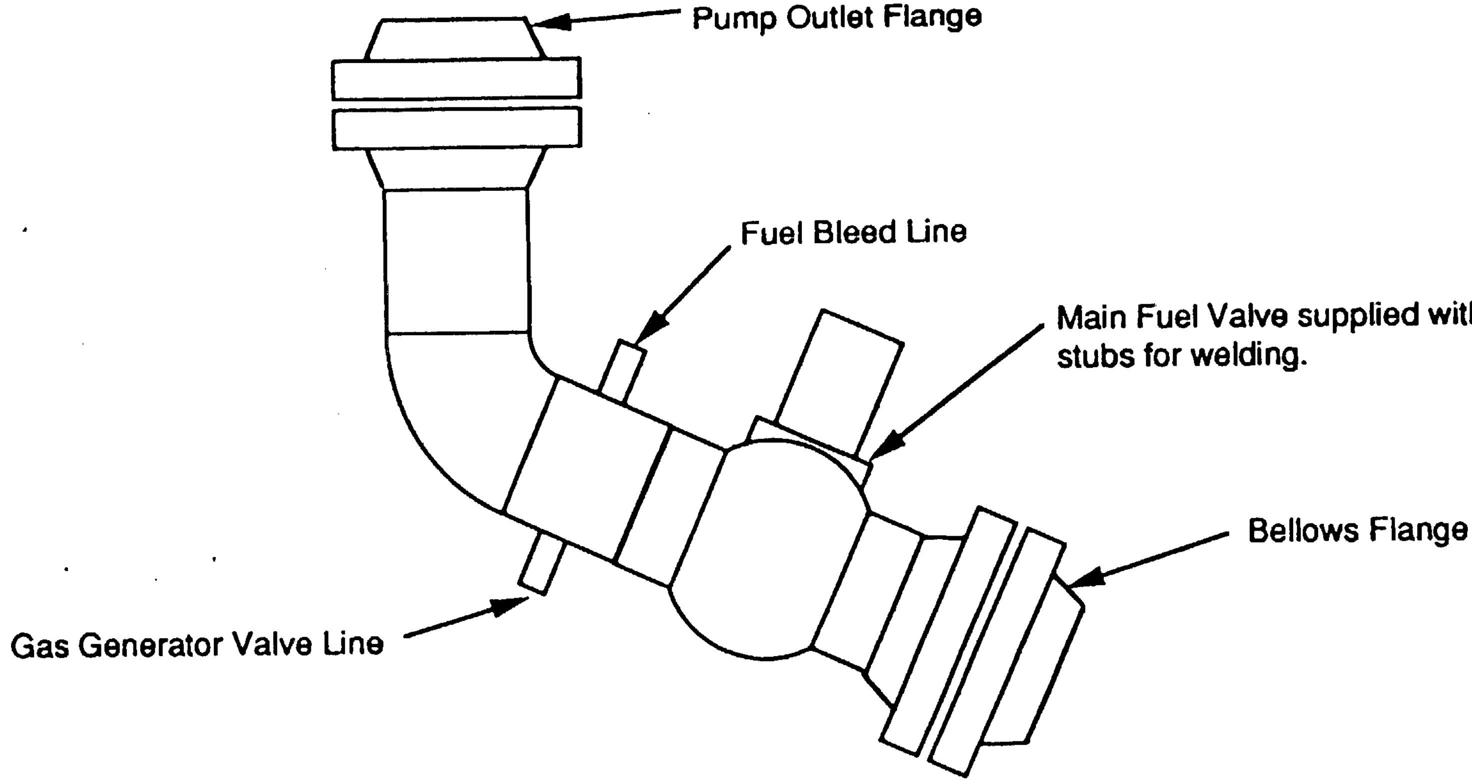
Effector Interfaces

Several design considerations were addressed to determine the best method of interfacing the engine controller with the propellant effector controller. These considerations, available options, and the rationale for the option selected were as follows:

Signal Format

Signal format defines how the information content of the signal is arranged. The two format options available are analog and digital. Analog format has been the more traditional approach in aerospace, although digital actuator technology is becoming more common. One drawback of the analog

• WELDING VALVE INTO SHORT MANIFOLD SAVES 2 PR. OF FLANGES SAVING WEIGHT AND COST WHILE INCREASING RELIABILITY



MAIN FUEL VALVE AND MANIFOLD SUB ASSEMBLY

Figure 3-4. Main Propellant Valves Welded Into Convenient Sub-Assembly

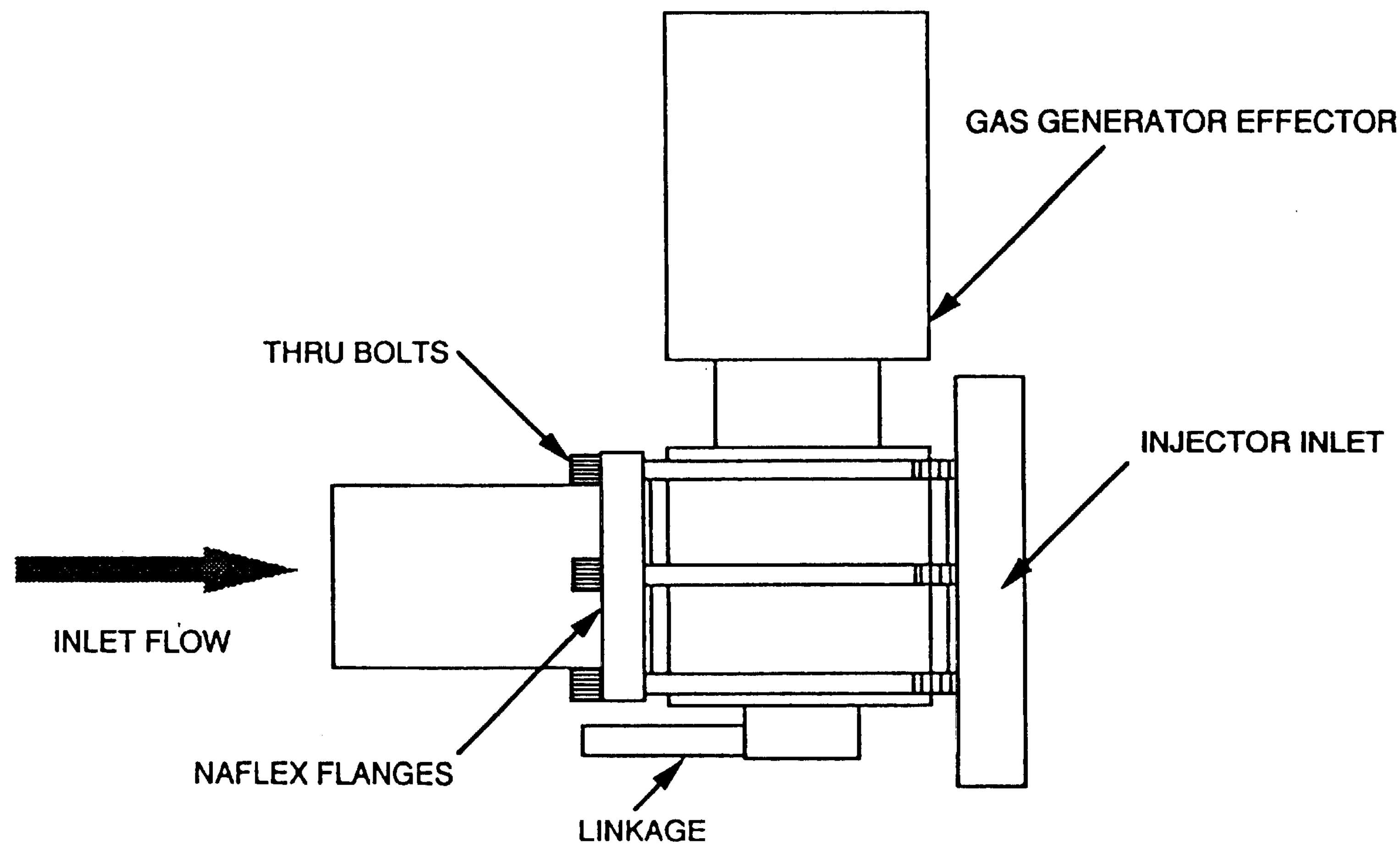


Figure 3-5. Gas Generator Valve Clamped Between Interface Flanges

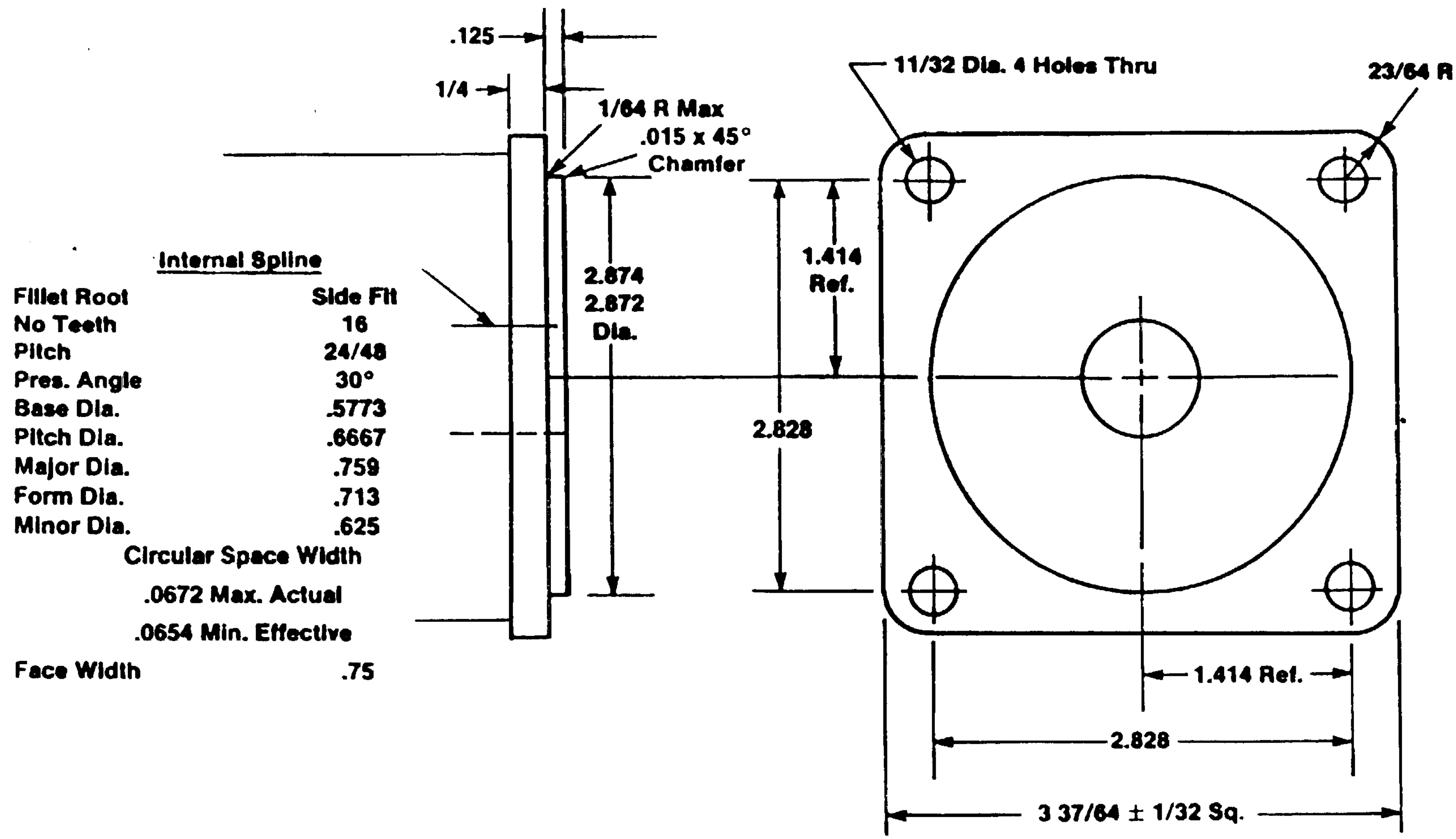


Figure 3-6. Actuator Interface

signal format is its high susceptibility to noise. The digital signal format is well-suited to noise cancellation techniques and has a high level command interface, i.e., does not require the engine controller to function as watchdog over propellant effector/valve details, simplifying the engine controller interface. Based on these considerations, the digital signal format was selected.

Transmission Format

The standard approaches are serial and parallel. The parallel method is inherently faster but requires more transmission paths and consequently more pins and therefore larger connectors. Since the rates for serial transmission are more than adequate and it offers higher mechanical reliability, lower weight, and a broader range of available standards, serial transmission was selected.

Method of Connection

The method of interconnection specifies the means by which several propellant effectors are linked to a single engine controller. The options are point-to-point and bused. A point-to-point approach dedicates one interface cable to each individual propellant effector separately. With a bused method, a single interface cable is daisy-chained from the engine controller to each of the propellant effectors in a network fashion. Commands are broadcast to all nodes of the system at once, the command format specifying which node is to respond.

The point-to-point method has the advantage of simple protocol and lower software overhead. In contrast, the bused method is more flexible, has a lighter cable harness and uses a single engine controller connector interface. The bused method is also easily expandable to additional effectors. These features make the bused approach the preferred method of interconnection.

Media

The two types of transmitting media were considered: wire and fiber optic. With the wire media three different approaches were considered:

- MIL-STD-1553B
- High Speed Data Bus
- RS-422 Multidrop

With the fiber optic media, three alternatives were considered:

- MIL-STD-1773

- High Speed Data Bus
- Fiber Distributed Data Interface

Of the wire media, MIL-STD 1553B is the high reliability, low risk approach. MIL-STD 1553B possesses the highest degree of standardization and is the most widely used method with over 10 years of experience in avionics.

Of the fiber optic media, MIL-STD-1773 offers the lowest risk approach with the highest degree of standardization. Fiber optics also provide lighter weight and higher noise immunity. The disadvantage with fiber optics is the questionable reliability in a high G environment. In addition, although a fiber optic standard is available, it lacks the maturity and broad application of MIL-STD-1553B. Therefore, MIL-STD-1553B was selected as the baseline.

Commonality Analysis

The use of common components for valves and actuators was considered because of the cost benefits of higher production rates of fewer parts. It was concluded that the fuel and oxidizer valves could be the same, as could the gas generator valves, with common actuators for all four valves.

3.1.3 Results

Common valves and EMAs were selected for the main propellant valves, which would be part of welded manifold subassemblies. Common gas generator valves and actuators were also selected; these valves would be clamped between mating flanges. The main propellant valves were sized for a 5 inch line and have eccentric 4 inch balls. The reduced bore gas generator valves were sized for a 1 inch line. Effector interfaces were based on digital signal format, serial transmission, bused interconnections, and hard-wiring per MIL-STD-1553B.

3.2 Preliminary Design

3.2.1 Objective

The objective of this task was to prepare a preliminary design of the effector consistent with the requirements identified above plus the program objectives of low recurring cost and high reliability. The design selection was to be supported by trade studies and analyses to identify major cost elements and evaluate options best suited to achieving low cost.

3.2.2 Activity Overview

The approach to this task was to combine industrial and aerospace practices for performance criteria, analysis methods, design features, material usage, manufacturing methods, etc. Special emphasis was placed on the overall program objectives of high reliability and low cost, leading to the following design principles:

Reduce parts count wherever possible
Incorporate electrical redundancy
Minimize/simplify mechanical and electrical interfaces
Use proven technologies
Provide design development flexibility

The baseline design of the main propellant effector is shown in Figure 3-7. Major constituent parts of the effector include redundant electronic assemblies, motor assembly, harmonic drive gear reducer, resolver assembly, and the main valve assembly. Design features are highlighted by Figure 3-8. Figure 3-9 provides further detail of the EMA components.

Redundant brushless DC motors provide power output. The motors are mounted on a common drive shaft and sized to provide sufficient torque to overcome the drag imposed should the other motor fail. The motor assembly includes duplex bearings. The motor assembly layout is shown in Figure 3-10. The harmonic drive provides 180:1 reduction of the motor output and was selected over alternative approaches because of its compactness and minimal parts count. The harmonic drive is presented in Figures 3-11 and 3-12.

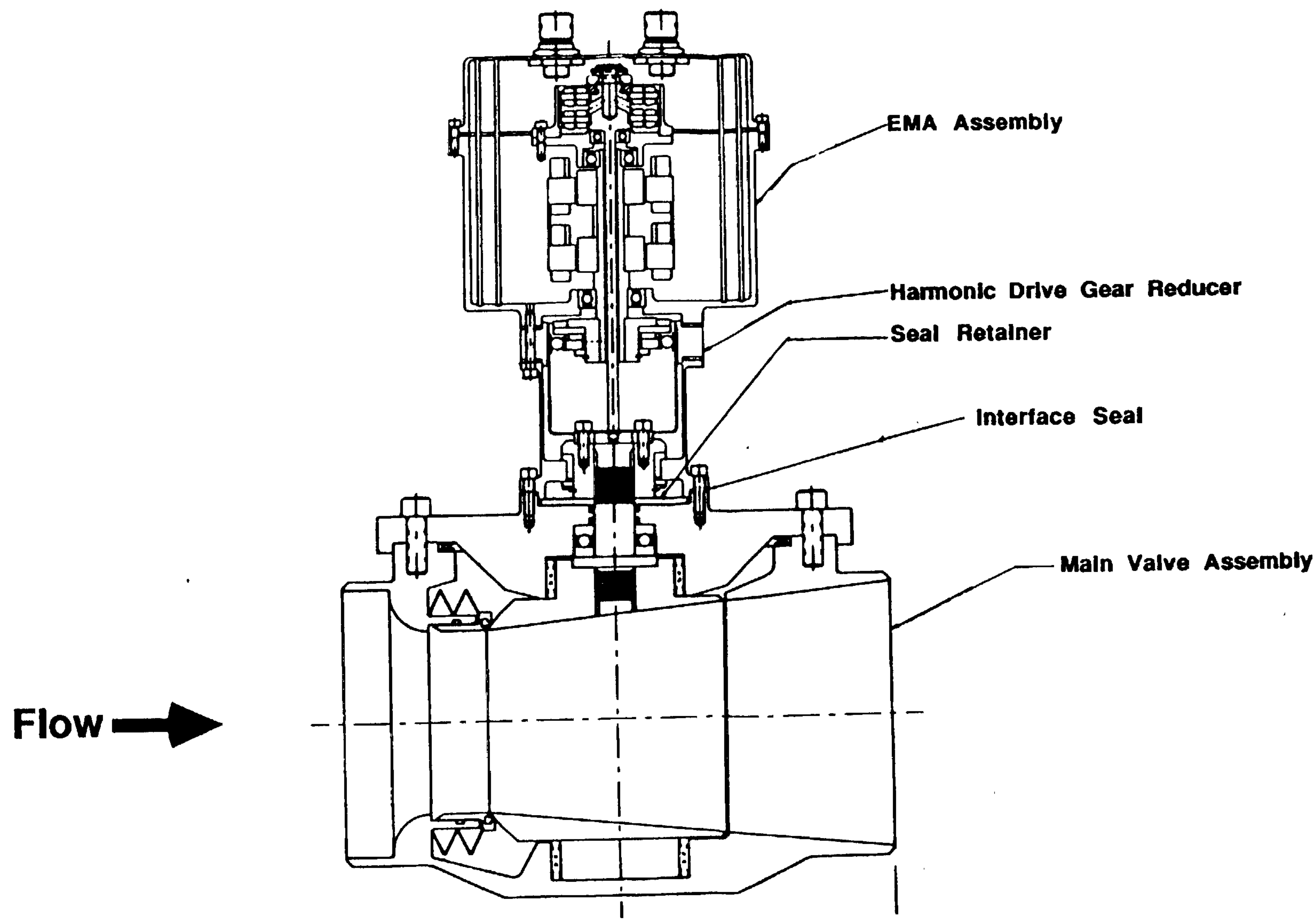


Figure 3-7. System Layout

- Valve Commonality (LOX And LH_2)
- Integral Valve Diffuser
- Actuator Commonality (Main Propellant And GG Valves)
- Redundant Motors And Electronics
- Integrally Mounted Dual Channel Motor Control And Drive Electronics
- Closed Loop Digital Control
- Serial Communication Interface (MIL-STD-1553B)
- High Ratio Single Stage Gear Reduction

Figure 3-8. Design Features

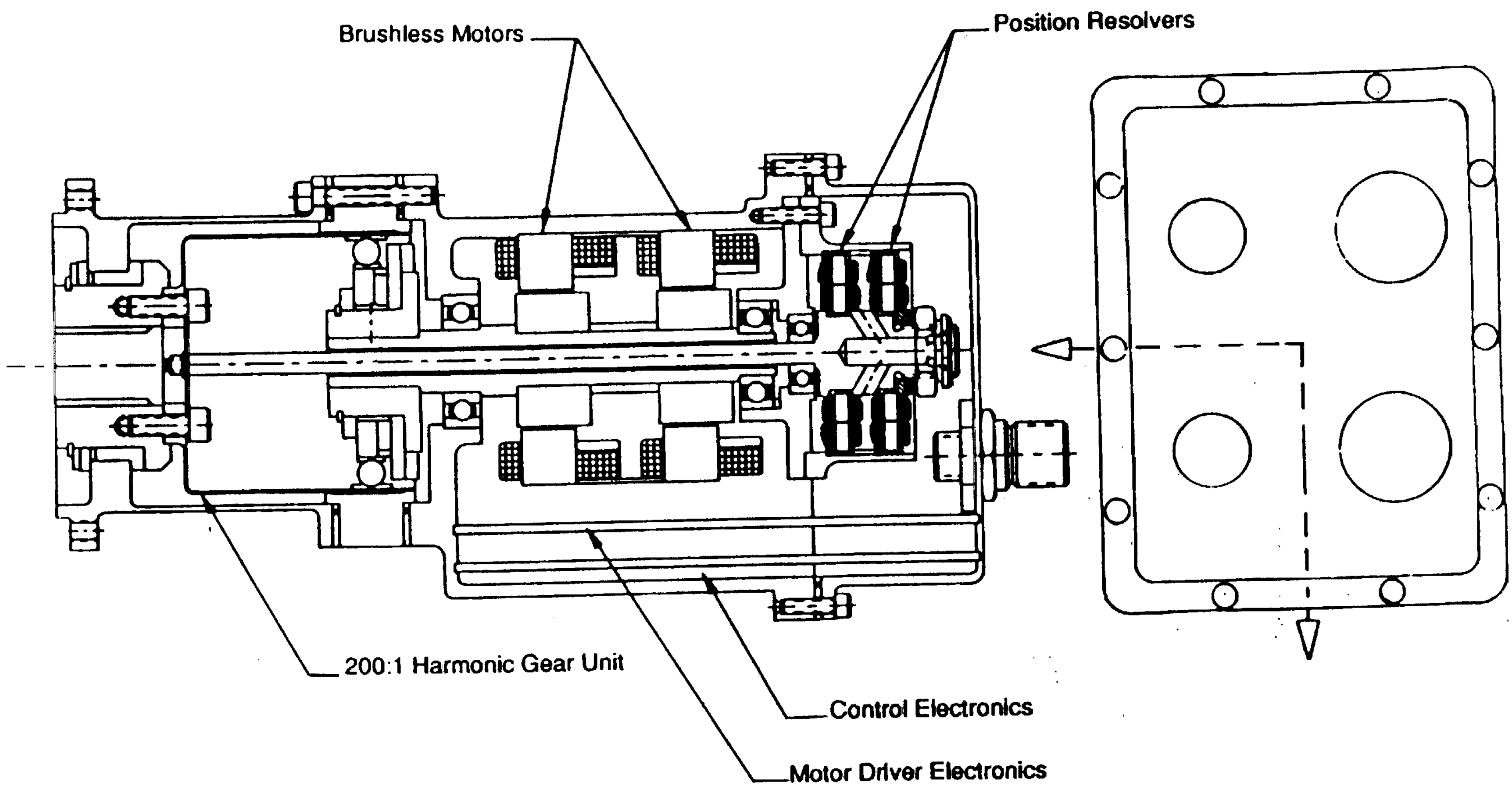


Figure 3-9. Electromechanical Actuator Assembly

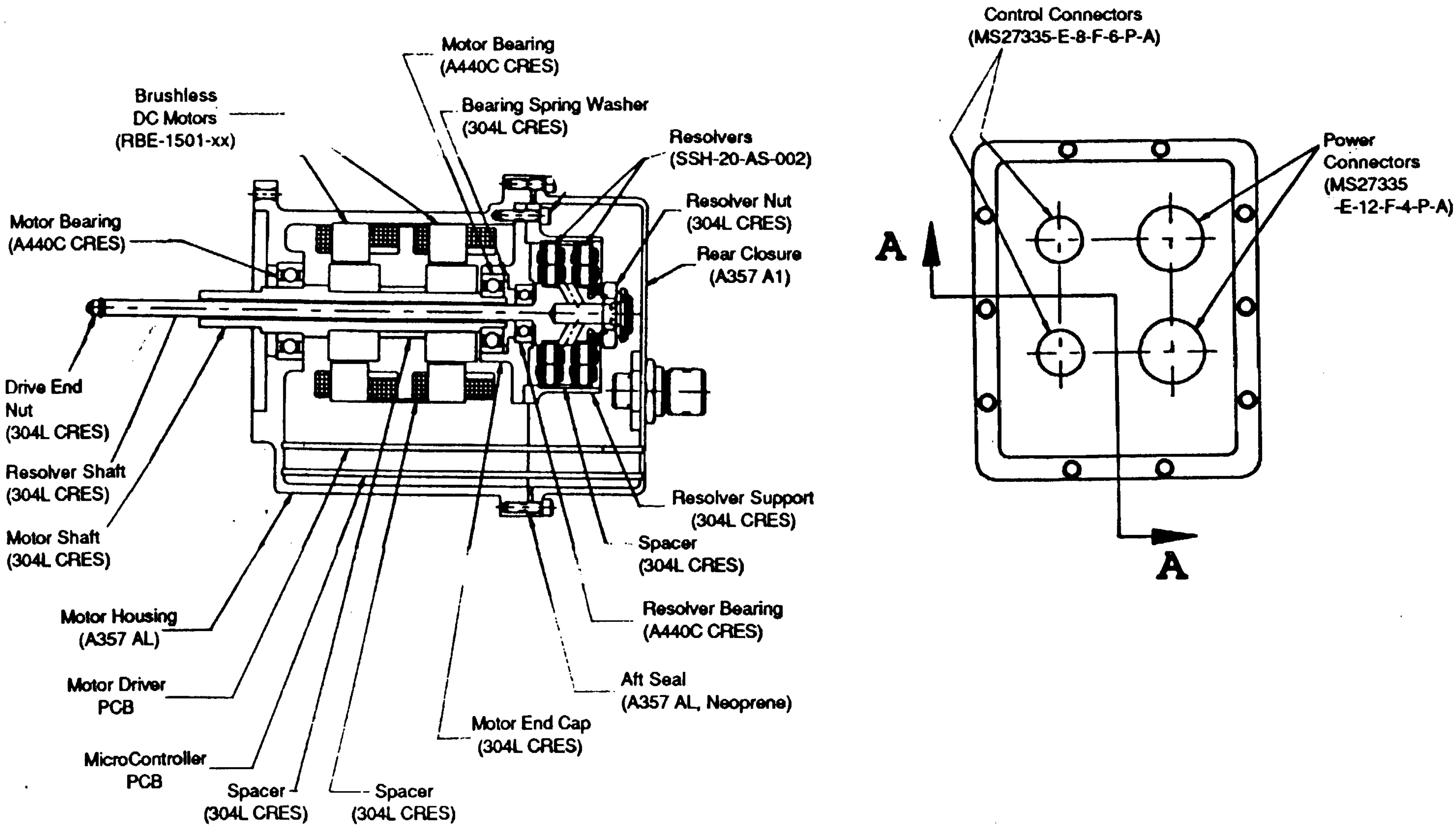


Figure 3-10. Motor Assembly Layout

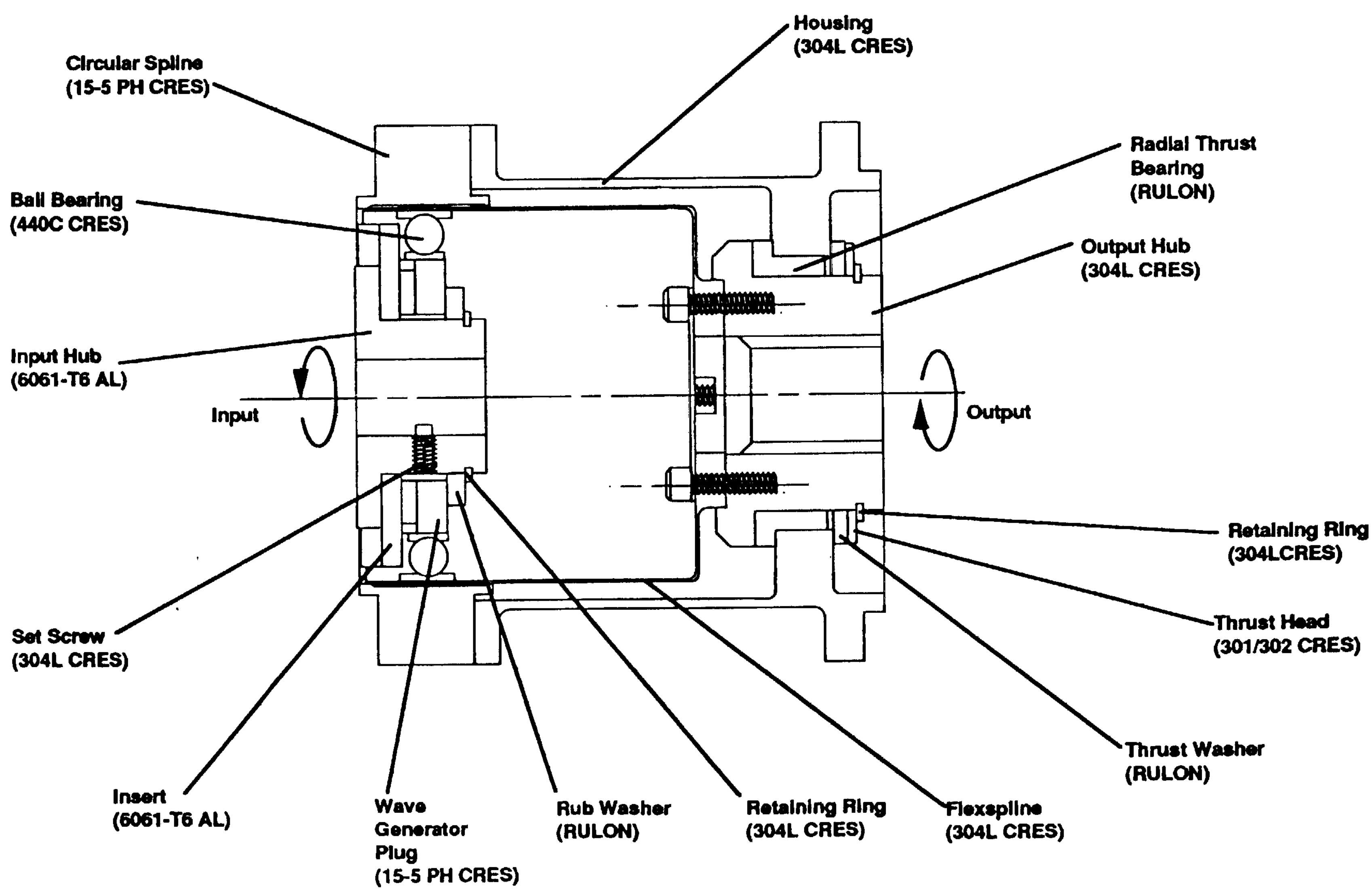
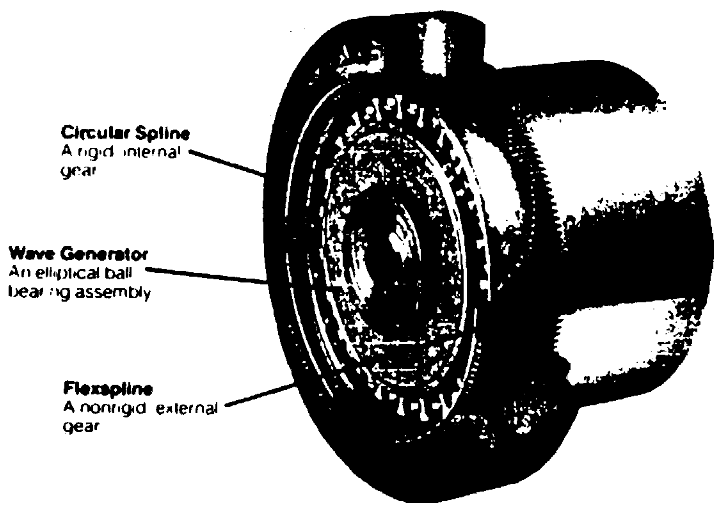


Figure 3-11. Harmonic Drive Layout



Features

- Single Stage Reduction
- High Torque Capacity
- High Torsional Stiffness
- Zero Backlash
- Compact Design

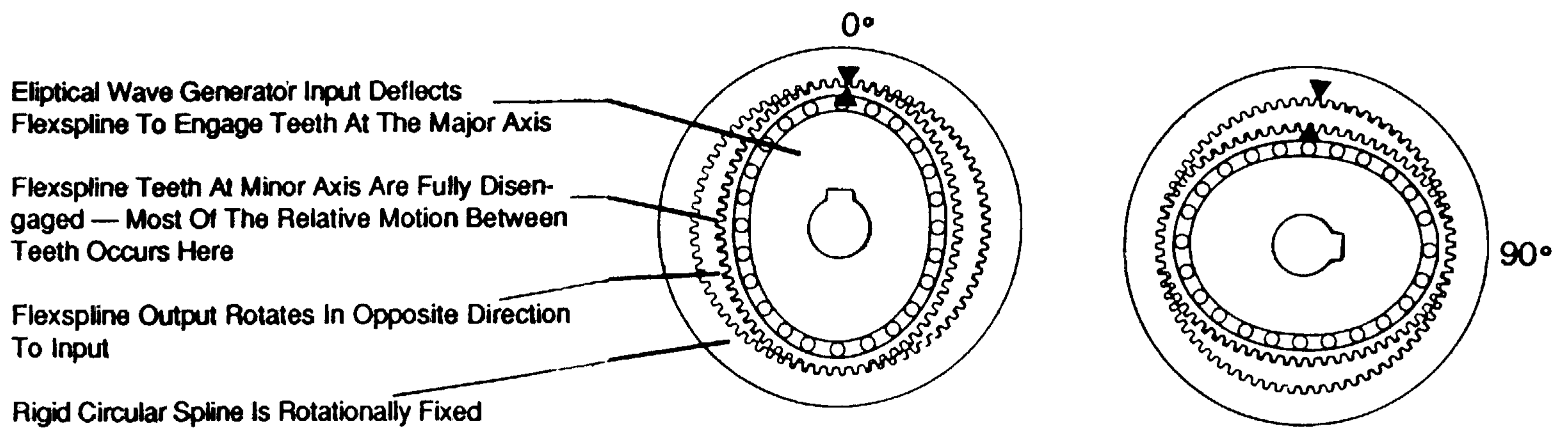


Figure 3-12. Harmonic Drive Assembly

The functional block diagram for the system is shown in Fig. 3-13; Fig 3-14 provides detail of the functional diagram within a single channel. There are two electronic channels which are completely isolated. Within each channel are two separate circuit card assemblies which perform the motor drive and control functions. Figure 3-15 shows the layout of the microcontroller printed circuit board.

3.2.3 Results

The Preliminary Design Review was conducted at MSFC on 27 September 1990. Included in the data package were the following:

DR-27	Design Review Package
DR-29	Drawings
DR-30	Effector Test Plan

Summary of Studies and Analyses
Reliability Failure Modes Analysis
Statement of Work/Requirement Documents
Fabrication Flow Charts
Cost Model Description.

3.3 Studies and Analyses

3.3.1 Objective

The objective of this task was to support the preliminary design activities through trade studies, engineering analyses, manufacturing process analysis, and laboratory tests to verify that candidate designs meet cost, fabricability, performance, and reliability goals. Historical reliability data were to be analyzed and necessary improvements to component reliablity identified.

3.3.2 Activity Overview

Numerous studies and analyses were conducted in support of effector design activities. The subjects and results of these efforts were as follows:

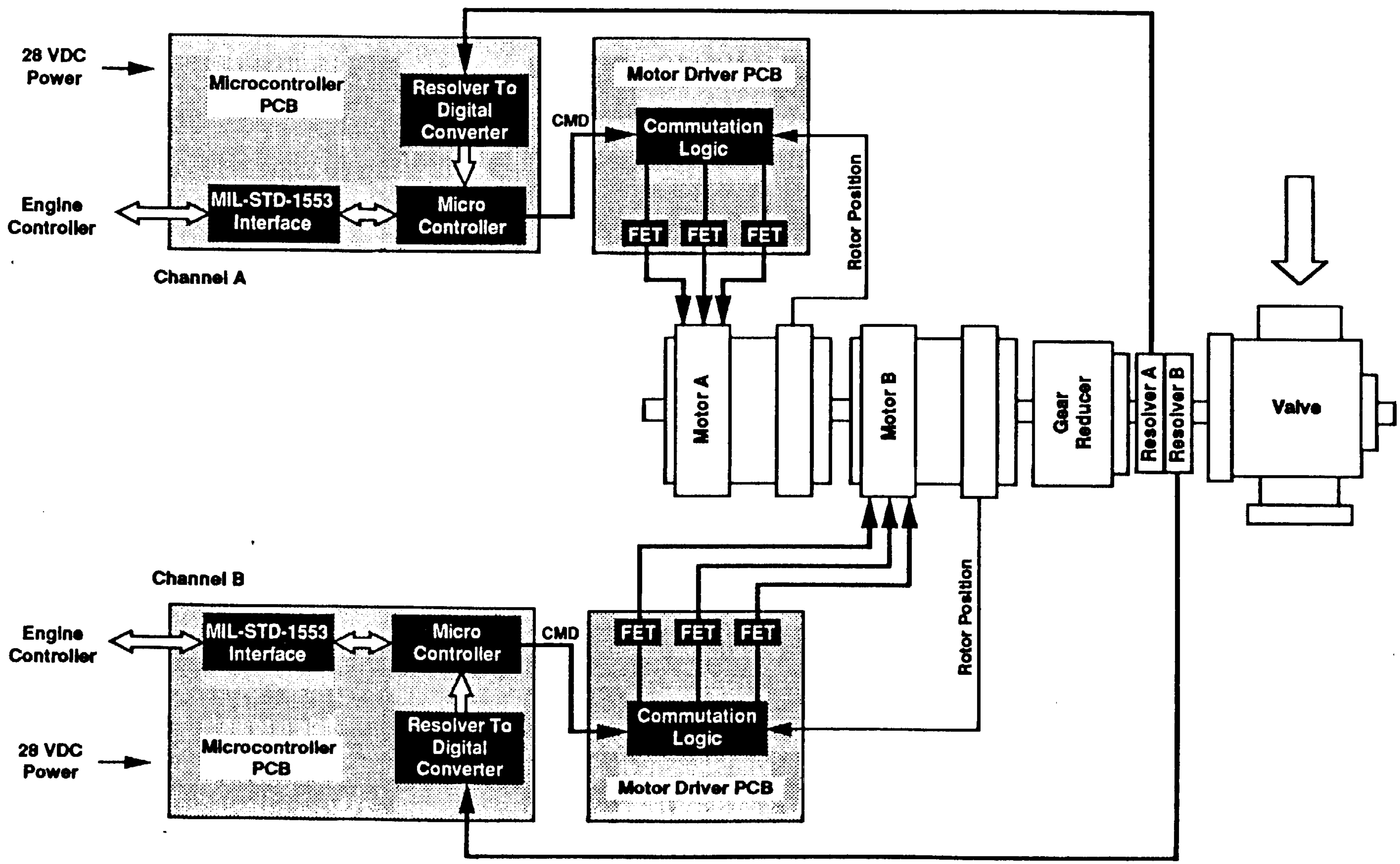


Figure 3-13. Functional Block Diagram

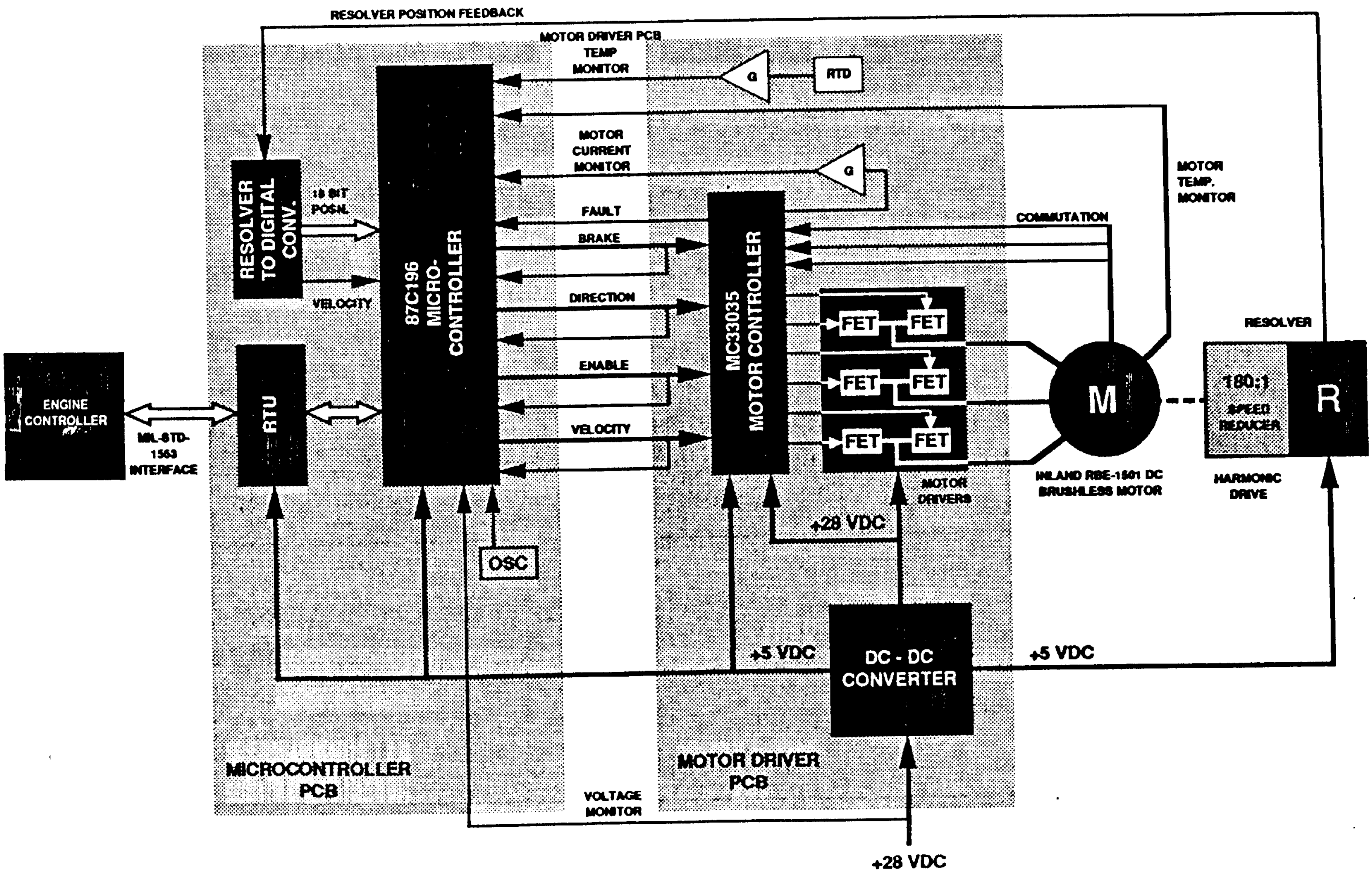
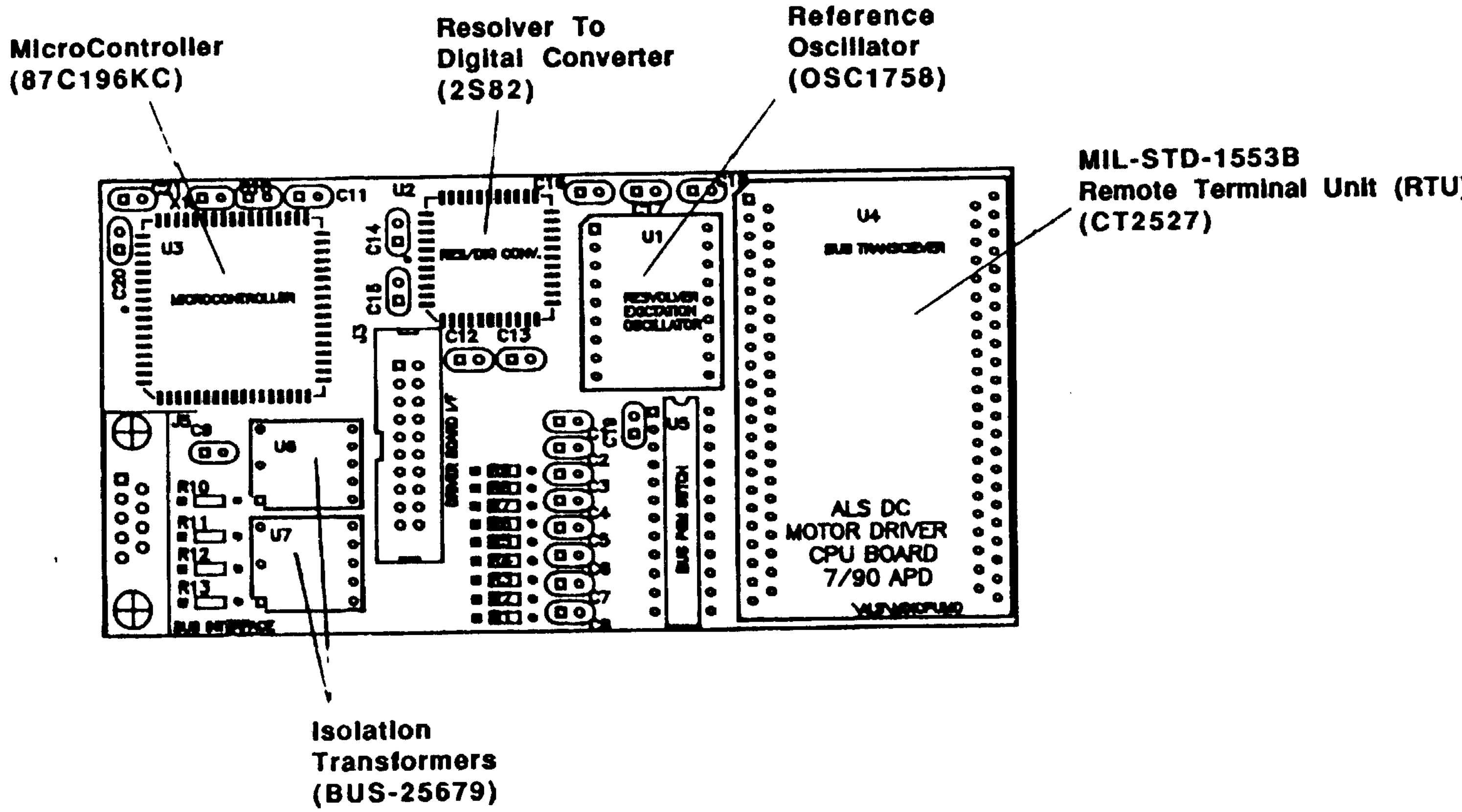


Figure 3-14. Function Diagram-Single Channel Detail



Board Dimensions: 2.500" x 4.875"

Figure 3-15. MicroController PCB Layout

Distributed Control System Architecture

The EMA design evolved from trade studies conducted at both system and component-levels. A key system-level trade was the selection of a distributed control system architecture. Advantages of this type of architecture are that it accomodates expandability of the control system as the engine design evolves. It simplifies the integration task by forcing resolution of design and operations problems earlier in the development cycle.

Selection of a distributed control system architecture drove the requirement for additional control authority within the EMA assembly. This meant providing local closed-loop control capability based on position commands received from an external source (i.e., engine controller), and providing the ability to sense and report status (health monitoring) during operation. These two features allow more autonomous EMA operation and enhance functional checkout at the actuator level.

Integrally Mounted vs Remotely Mounted Electronics

A key component-level trade study was the selection of integrally mounted versus remotely mounted electronics. Remote mounting allows the electronics to be more effectively isolated from the engine environment but requires additional cabling, connections, packaging and mounting hardware. This adds weight and complexity, reduces reliability, and makes installation and maintenance more difficult. By integrally packaging the electronics with the other EMA components (motors, gearing, etc.) and properly designing for thermal, vibration and shock effects, a simpler and more modular packaging design was achieved.

AC Induction vs DC Brushless Motor

A trade study compared an AC induction motor to a DC brushless motor. The AC motor was sized to have a pull-out (maximum) torque which closely matched the maximum torque of the DC brushless motor. If an AC motor is used, some type of slip control would be required to assure that the motor would not pull out of step and lose its peak torque capability. Figure 3-16 shows the

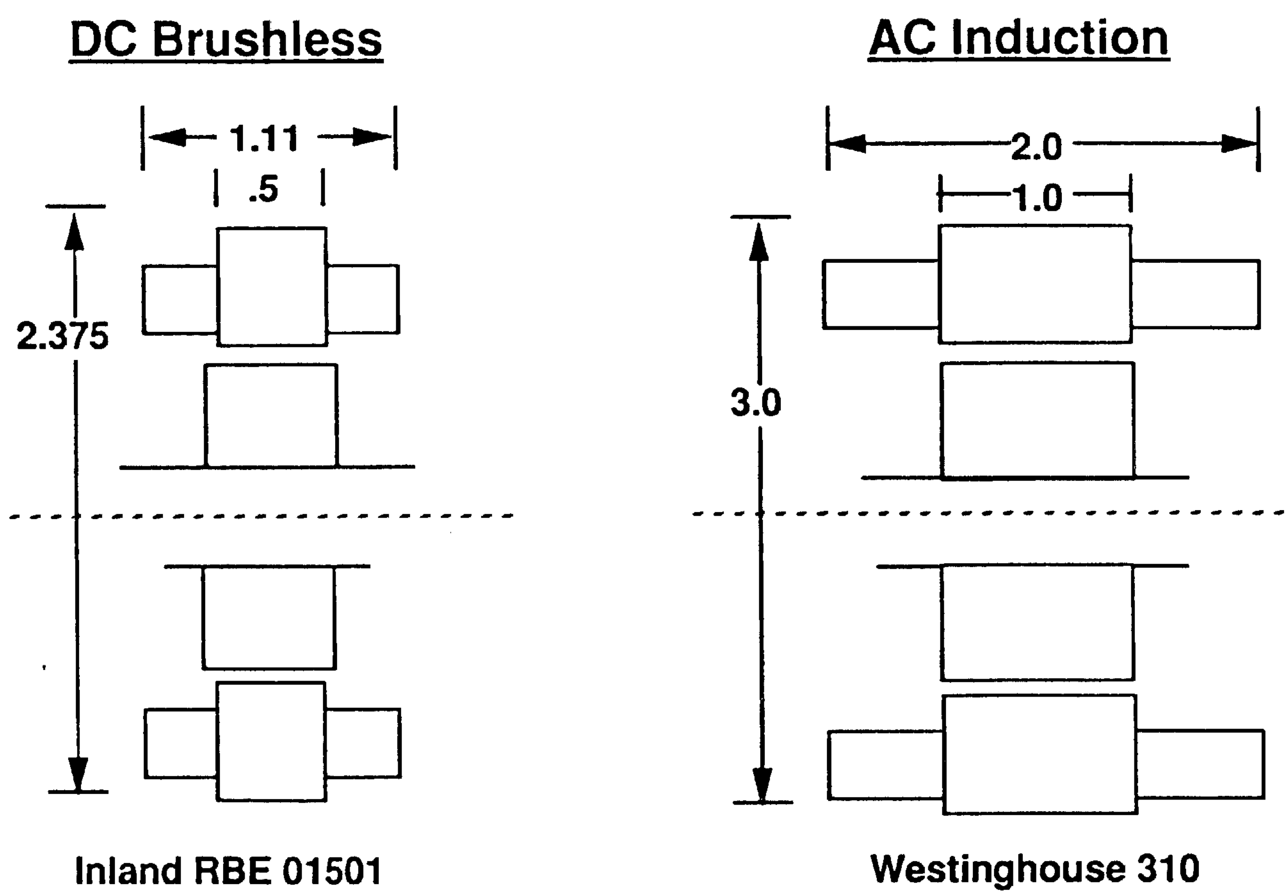


Figure 3-16. AC Induction Versus DC Brushless Motor

relative size of the AC induction motor vs the DC brushless motor. A comparison of characteristics is shown in Figure 3-17. The AC motor is significantly larger and heavier than the DC brushless motor. Other significant differences are that: the DC brushless motor has a position holding capability when one winding is excited while the AC motor does not; the DC motor will cause a significant drag on the system with a short circuit winding failure while the AC motor is passive during this type of failure; the AC motor would be expected to respond more slowly because of its higher rotor inertia.

The DC brushless motor was selected for the preliminary design. Its primary disadvantage, the drag imposed by a shorted winding, was circumvented through proper sizing of the motors.

Analog vs Digital Control

Signal format defines how the information content of the signal is arranged. The two format options available are analog and digital. Analog signal format has been the more traditional approach in aerospace but has the drawback of high susceptibility to noise. Digital signal format is well suited to noise cancellation techniques and has a high level command interface, simplifying the engine controller interface. Digital signal format was selected.

Actuator/Engine Controller Interface

Several considerations were addressed to determine the best method of interfacing the engine controller with the propellant effector controller. Selected approaches and rationale for selection were as follows:

Signal Format: Digital format was selected over analog format because because of noise cancellation techniques and the high level command interface

Transmission Format: Serial transmission was selected over parallel transmission because of higher reliability, lower weight, and a broader range of available standards.

Method of Connection: The bused method was selected over the point-to-point method because of greater flexibility, lighter cabling, and single controller connector interface.

	DC Brushless	AC Induction
Diam Over Lamination	2.375	3.0
Length (Stack)	.5	1.0
Length (Over Windings)	1.1	2.0
Weight (oz)	9 oz	30 oz
Poles	12	6
Max Torque (oz in)	174	180
Rated Torque (oz in)	103	103
Speed (RPM)	4500	4500
Frequency (Hz)	450	250
Voltage (Inverter Input)	24VDC	24VDC
Current (Amps DC)	12.4	14.2
Rotor Position Feedback	Yes	Yes (1)
Holding Capability	Yes	No
Shorted Winding Losses (Drag)	Yes	None

(1) Motor Speed Feedback For Slip Control

Figure 3-17. DC Brushless Motor Selected

Media: Hard-wiring per MIL-STD-1553B was selected over fiber optic media because of widespread use in avionics and concerns about effects of high G loading with fiber optics.

Valve interfaces: The selected design approach was to make the main propellant valves part of welded manifold subassemblies and the gas generator valves flanged units clamped in place by through-bolts between two mating flanges.

Separate vs Actuator-Mounted Electronics

Actuator-mounted electronics were selected, due to increased reliability and reduced costs. Figure 3-18 shows the trade study considerations involved in this selection.

Encoder vs Resolver Position Transducer

The resolver was selected due to its robustness and proven performance in aerospace applications. Figure 3-19 shows the trade study considerations involved in this selection.

Flanged vs Flangeless Gas Generator Valve Design

The flangeless design was chosen based on slightly lower cost and weight, acceptable bolt interfacing, and structural considerations.

Main Valve Concentric vs Eccentric Ball Design

The eccentric ball feature for the main propellant valves was selected because of lower overall cost resulting from reduced torque and smaller motors with the eccentric design.

Gas Generator Valve Sizing

This trade study addressed the gas generator ox valve configuration options of smaller bore size versus a smaller valve. Commonalitity of the ox and

Criteria	Separately Mounted	Actuator Mounted
Complexity	Additional Cabling/Connectors Required	Limited Connections Enhance Reliability
	Separate Electronics Enclosure Required	
	Additional Electronics Mounting Pads Required On The Engine	
Size/Weight	Less For Each Valve/Actuator Assembly	Less For Total Engine System
Environment	Control/Drive Electronics Can Be Be Mounted In Less Hostile Environment	Packaging Design Must Acccount For Environmental Extremes
Checkout	Verification Of Electronics Separate From Motor	Verification Performed By Built-In-Test And Status Monitoring

Actuator Mounted Electronics Selected Due To Increased Reliability And Reduced Costs

Figure 3-18. Separate Versus Actuator-Mounted Electronics Trade Study

Criteria	Encoder	Resolver
Absolute Position Measurements	Yes	Yes
Output Format	Digital	Analog
Interface	Interfaces Directly To The MicroController	Requires Additional Electronics
Resolution	Discrete (12 Bits)	Inifinite
Complexity	Few Parts. Optical Sensors Fed Directly To MicroController	Requires Excitation Input Signal And Output Signal Demodulation
Velocity Signal	Inadequate At Low Speeds	Provides Analog Velocity Signal
Construction	Susceptable To Vibration And Temperature Variations	Rugged Mechanical Construction. Resistant To Humidity And Dust Effects

Resolver Selected Due To It's Robustness And Proven Performance In Aerospace Applications

Figure 3-19. Encoder Versus Resolver Trade Study fuel valves is desirable for cost reasons. It was concluded that common valves are possible with proper design of valve admittance characteristics.

<u>Floating vs Trunion Mounted Ball</u>

This study compared a floating ball design against a trunnion-mounted design and concluded that the potential for nonuniform wear and subsequent leakage with the floating ball made it unacceptable.

Experimental Studies

In addition to the above analytical studies, experimental work was performed early in the program to verify the analyses and resolve any potential problems prior to hardware fabrication. The following testing was performed:

Gear reducer: In support of gear reducer development, two prototypes were built and tested to verify compliance with torsional stiffness, backlash, and load requirements at the required operating speeds. One of the units was also tested at cryogenic temperatures to evaluate the effects of temperature on efficiency, to characterize the thermal resistance across the reducer, and to verify operation at low temperatures. Test data were combined with thermal model data to verify that temperatures in critical locations were within safe operating ranges. Figure 3-20 shows the test fixture used for these tests.

Brushless DC motors: Tests were performed on shaft-coupled DC motors to evaluate the speed-torque characteristics at various supply voltages. Also characterized was the amount of drag torque imposed on the system under a worst-case short circuit condition in one of the motors. These data were used to perform final motor sizing and selection. Figure 3-21 shows the motor test set-up.

Electronic circuitry: The electronic circuitry was breadboarded and tested with the motor and resolver to verify both the interface and functionality. This circuitry also supported code development for critical portions of the firmware such as the resolver interface driver, motor interface driver, and the position control loop algorithm.

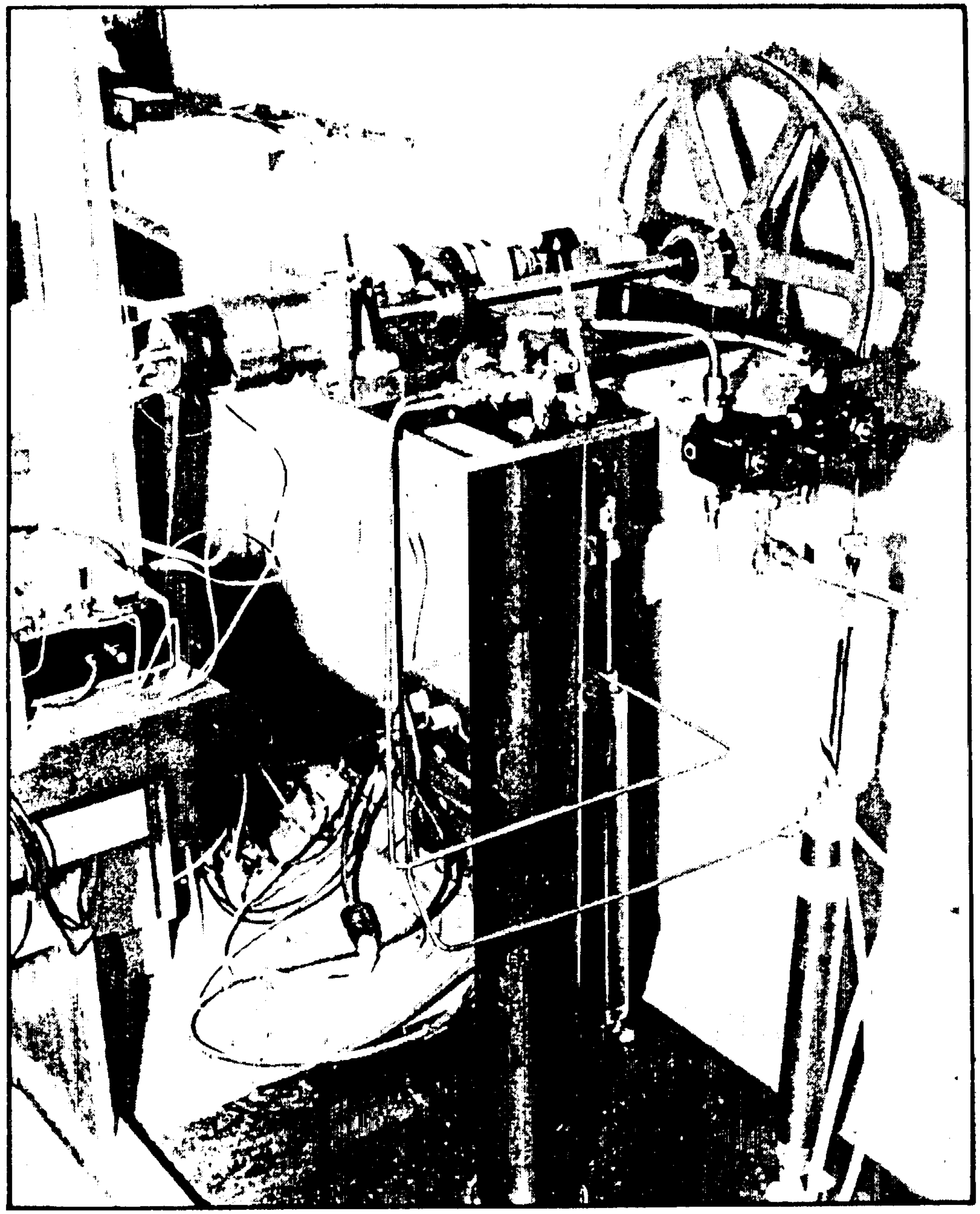


Figure 3-20. Test Fixture Close-Up

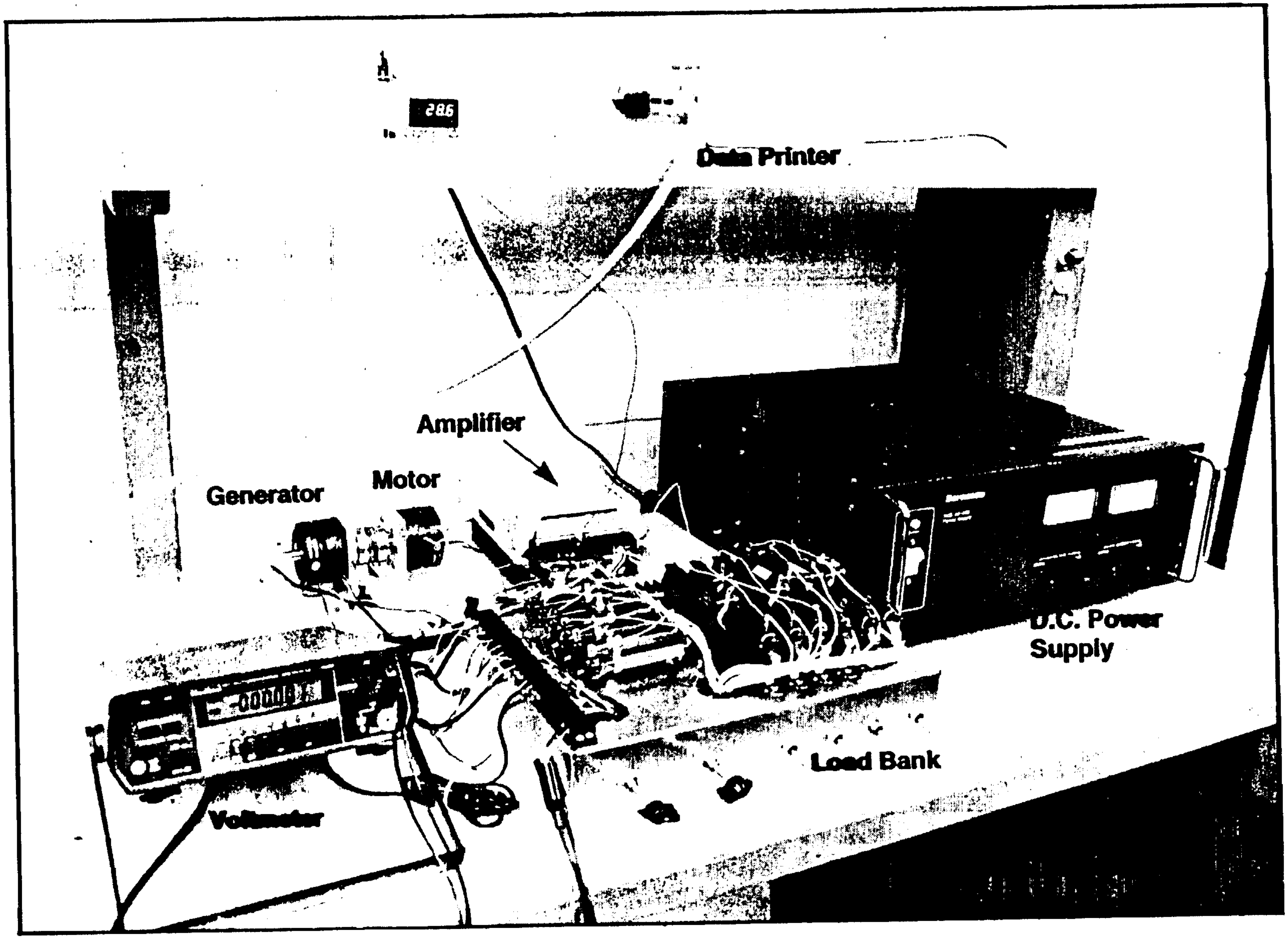


Figure 3-21. Motor Performance Test Set-Up

Brassboard EMA: A brassboard EMA was assembled from the component test hardware and tested. Step command tests were performed under various load conditions to evaluate position and velocity response, and to evaluate accuracy and repeatabiltity. Frequency response tests were performed to determine the gain and phase characteristics over a range of frequencies. The breadboard test fixture is shown in Figure 3-22.

3.4 Technology Development Program Plan

3.4.1 Objective

The objective of this task was to develop and implement a plan to develop technologies in both design and fabrication which would be too immature to incorporate in demonstration hardware but could be developed in time for and yield significant cost reductions in the Phase C/D engine components. Selection of candidate technologies was to be based on potential payoff and development risk.

3.4.2 Activity Overview

Two development plans were generated. These are summarized on Figures 3-23 and 3-24.

3.4.3 Results

The results are presented above.

3.5 Cost Model

3.5.1 Objective

The overall objective of this task was to construct a cost model capable of predicting recurring costs of a flight effector system, including production and operations and support (O&S) costs, at production rates of 30 to 100 units per year. The model was to consider the impact of various specification requirements as well as production rate and learning curve effects and to reflect

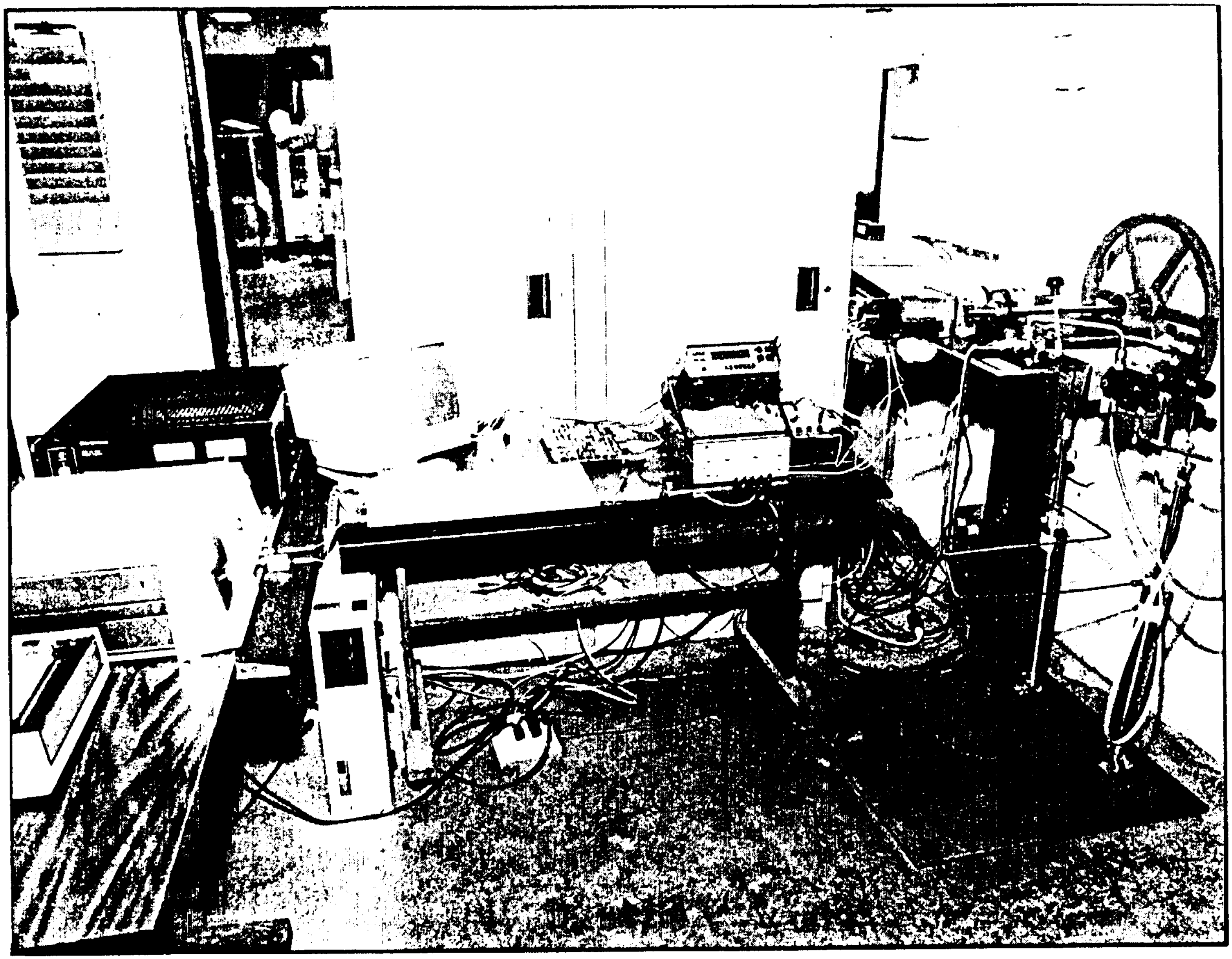


Figure 3-22. Actuator And Test Fixture Set-Up

Software Controller DC Motor Commutation

OBJECTIVE: Directly Commutate The DC Motor Through Software To Increase Reliability And Reduce Cost Through Eliminating Circuitry Currently Dedicated To The Commutation Task

APPROACH: Develop Software Code Which Accepts And Interprets Signals Received From The Motor Hall Effect Sensors And Generates Output Signals Required To Provide Six Step Full Wave Commutation

Design, Fabricate, And Demonstrate Through Test A Single PCB Which Combines The MicroController And A Hybrid Package Which Contains A Triple H-Bridge Drive Configuration And DC To DC Power Conversion

PAYOFF: This Program Will Eliminate The Motor-Driver Board And Its Components And Will Take Advantage Of The Capabilities Of The MicroController. The Following Parts Will Be Eliminated:

- Motor Controller
- DC-DC Converter
- H-Bridge Transistors And MOSFETS
- Supporting Resistors, Capacitors, And Diodes

While Only This Part Will Be Added:

- Single Chip Motor Driver Hybrid

Figure 3-23. Technology Development Program Plans

All Welded Valve

OBJECTIVE:	Eliminate Bolted Bonnet And Accept The Valves Through Fracture Mechanics Analysis And Proof Testing
APPROACH:	Conduct Finite Element Analysis Of The Valve Stresses Along With A Fracture Mechanics Analysis To Show That Proof Testing And Ultrasonic Inspection Is Adequate For Acceptance
	A Cost Analysis To Show Advantage Of A "Throw-Away" Valve vs. A Reworkable Valve
	Demonstration Testing Of A Sample Welded Valve With Introduced Critical And Subcritical Flaws To Show That Adequate Acceptance Testing Is Possible Without Radiographic Examination
PAYOFF:	A Lower Cost Valve (Fewer Parts And Less Assembly Effort) And No Spare Parts Other Than Valves Required. Also, There Would Be No Depot Maintenance System Required For The Valves

Figure 3-24. Technology Development program Plans, continued

cost estimates made in the design process as well as actual costs of fabricated hardware. The model was intended for use in subsequent evaluations of cost reduction design and manufacturing approaches.

The objective of the Phase I effort was to define general model structure, requirements, underlying assumptions, data sources, and calibration approach based on actual fabrication costs experienced, and to create a preliminary cost model.

3.5.2 Activity Overview

During Phase I, various spreadsheet software options were evaluated and Microsoft Excel was selected as the core application. This program permits data transfer between Macintosh and IBM PCs and has multiple windowing capability with customized menus and dialog boxes. A Supplier Cost Information Form was developed to collect supplier cost data in a consistent manner, with the intent of using this same form in other Aerojet NLS Advanced Development Programs. The Phase I activity culminated in a detailed presentation of program objectives, logic, features and cost model work at the Preliminary Design Review.

The model logic is shown in Figure 3-25. Touch labor and supplier costs for all constituent parts were to be inputted and continually updated as actual costs became available. Using algorithms developed, the model accounts for the variables cited above.

When cost model activities ceased in response to GFY 1990 and 1991 funding reductions, cost model logic had been updated and development of uncertainty algorithms was 90% complete. A data dictionary was also prepared. It included definitions used in model software, as well as all algorithms, and formed the basis of a Preliminary Users Manual. Preliminary software programming was completed but not checked out/validated. Record layouts (monitor screens) were formulated.

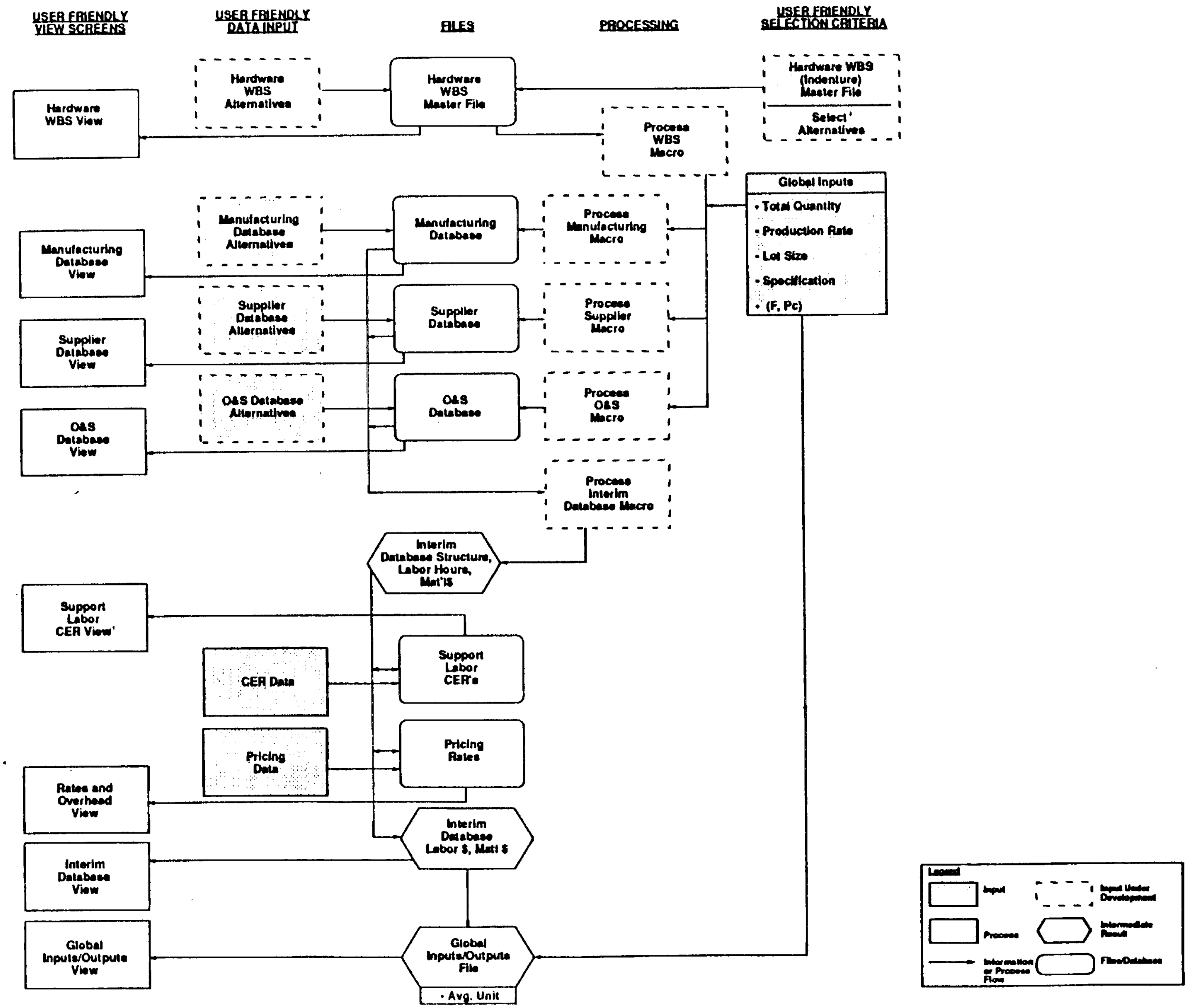


Figure 3-35. Cost Model Logic

3.5.3 Results

Cost model development work defined and partially developed a tool for analyses and tracking of STME engine component costs. Model logic, algorithm formulation, and basic programming were completed. Model operation was demonstrated using preliminary cost data derived from existing Aerojet-produced flight hardware. Model development was discontinued after Phase 1 of the program was completed.

The model, although not fully validated, is a potentially useful tool for similar cost studies in future programs. Since it is based on actual or estimated costs for given manufacturing process flows and specification requirements, rather than on historical data or simple cost estimating relationships, it is suitable for studying new manufacturing approaches or more broadly, new ways of doing business.

3.6 Detailed Design

3.6.1 Objective

The objective of this task was to prepare a detailed design and analysis of the propellant effector system and any GSE or STE required to install and operate the system at MSFC. A test plan (DR-30) for verifying the design was to be prepared; the plan was to include instrumentation requirements and a preliminary test matrix. Also, component reliability was to be estimated considering life-critical failure modes and uncertainties in the analysis.

3.6.2 Activity Overview

The detailed design was based on the preliminary design discussed in Sect. 3.2 above. Detailed design and analysis of all mechanical and electrical aspects of the EMA, including firmware and ground support equipment (GSE), was completed. Detailed thermal analyses were conducted and calibrated to experimental test results. Detailed structural analyses were also conducted; these addressed both thermal and mechanical loads including vibrational loads. An analytical model of the EMA was developed as reported above. Reliability was also addressed; a Failure Modes and Effects Analysis was prepared.

3.6.3 Results

The Detail Design Review was conducted at MSFC on 9 and 10 October 1991. Included in the review package were the following:

DR-20	Acceptance Plan
DR-23	Materials Control Plan and Usage Entry
DR-26	Contract End Item Specification (Hardware)
	Contract End Item Specification (Software)
DR-27	Design Review Package
DR-28	Interface Control Document
DR-30	Test Plan
DR-37	EEE Parts List

Vibration Analysis Reports
Stress Analysis Report
Thermal Analysis Report
Reliability Analysis Report

3.7 Servo Analysis and Control System Model

3.7.1 Objective

The objective of this task was to develop control system models and to conduct a detailed servo analysis to select and size forward gains, feedback gains, and shaping networks required to provide adequate gain and phase mangins; included in the analysis were propellant valve seal loads, fluid flow loads, and valve inertia.

3.7.2 Activity Overview

A control system model was constructed to reflect the block diagram of the actuator and represent the motor, gear reducer, and controls, employing equations to provide a mathematical description of the system dynamics. Figure 3-26 shows the analytical model, which was run both as a PC version and an

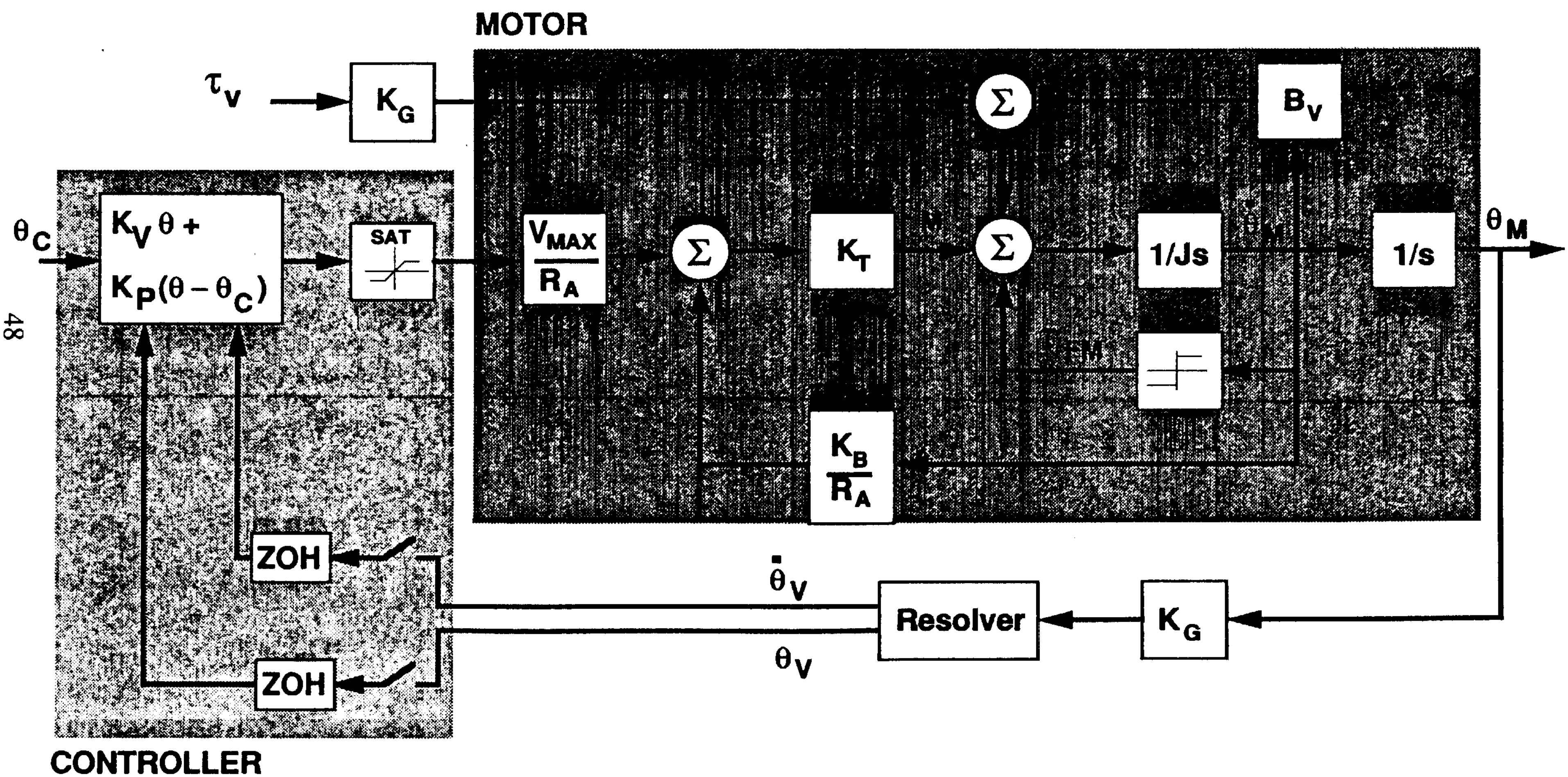


Figure 3-26. The Analytical Model For The EMA Has Been Defined

AD100 version. The latter ran in real time and was used to evaluate both step response and frequency response. Figure 3-27 shows a typical response to a step input as calculated by the PC version.

3.7.3 Results

Task results were presented at the Detailed Design Review.

3.8 Other Tasks

Other tasks in the WBS were not undertaken due to directions to stop work and subsequently to descope the program. As a result, the following tasks were not performed:

Fabrication and Evaluation
Detailed Cost Model
Special Studies
Technology Development Program Plan.

4.0 FUTURE DATA/HARDWARE APPLICABILITY

4.1 Overview

This program has evolved and/or proven a number of innovative approaches to the design, manufacture, and test of cyogenic propellant effector devices. Although these were designed to apply specifically to the NLS Main Engine (STME), the products of this program should be applicable directly or indirectly to other future NASA engine programs, either for upgrading existing designs or for entirely new engine types.

4.2 Data

Technical: The detailed design package and limited experimental data obtained early in the program provide a valuable background for future technical activity.

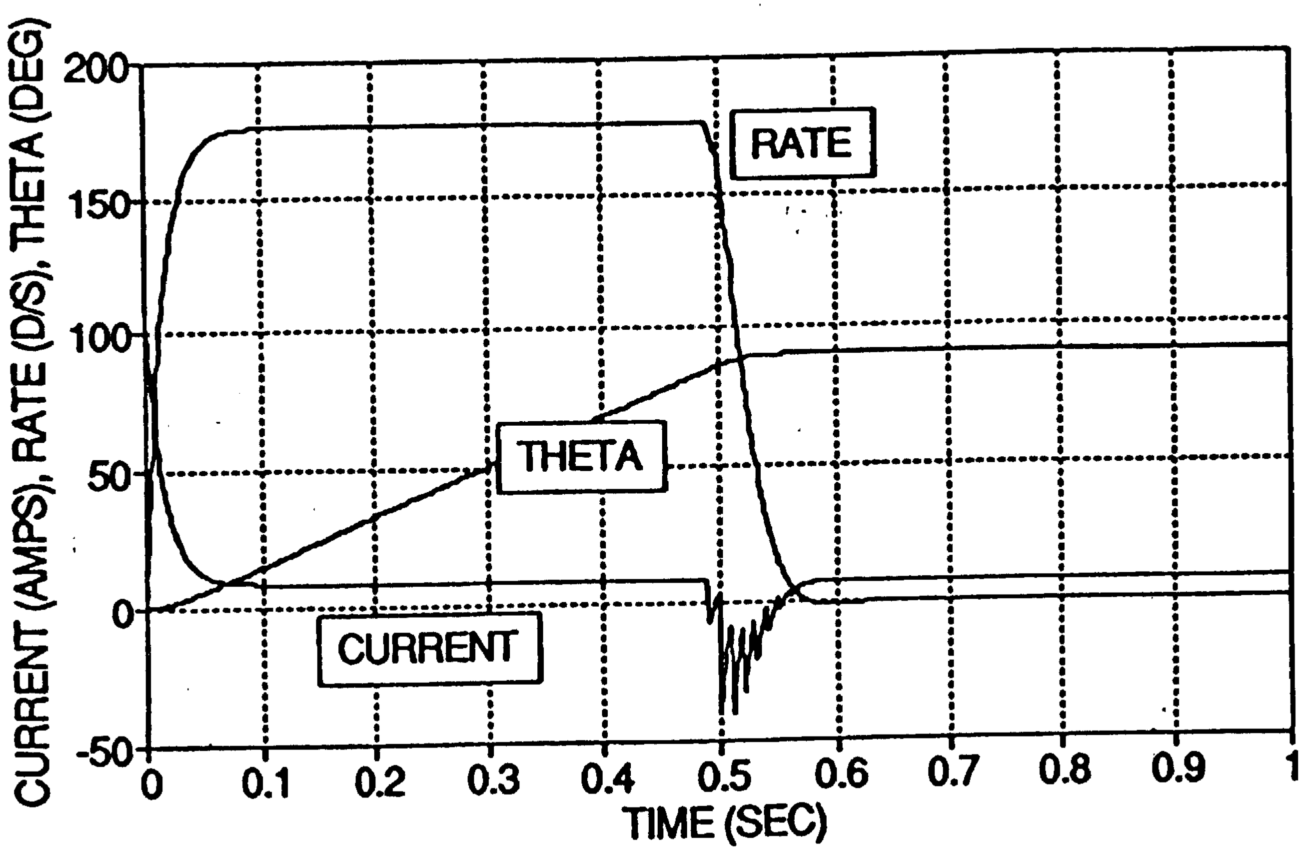


Figure 3-27. Typical Step Response Obtained From PC Simulation Of The Model

Cost Model: The cost model is likewise the foundation of an excellent tool for estimation, tracking, and control of recurring costs. The model has broad applicability to any component assembly and allows the user authority over input costs and manufacturing cost relationships. Development of a standard tool to be used by NASA and its contractors would be beneficial to all programs.

4.3 Hardware

The hardware design approach defined and to some extent corroborated in the program is generally applicable to flight propulsion systems and offers major cost advantages over commonly used hydraulically actuated valves, namely the elimination of an entire fluid system and associated contamination and leakage problems, reduced weight, reduced parts count, higher reliability, reduced manufacturing cost, reduced servicing in operation and thus reduced support costs.

5.0 RECOMMENDATIONS

It is recommended that the data and hardware future application potentials discussed in Section 4 be given consideration by NASA. In the case of the data, there are significant contributions to NASAs liquid rocket engine data base. In the case of residual hardware from the program, much valuable data could be gathered by completing the planned tests and/or specific assistance to future NASA engine program(s) could be obtained by adapting this hardware.

6.0 REFERENCES

Table 6.1 provides a listing of all Data Requirements (DRs) submitted.

Table 6-1 List Of References

Data Requirements (DRs):

03	Monthly Progress Report
04	Facility Plan
06	Government-Furnished Property Plan
15	Technical Implementation Plan
16	Logic Network And Key Milestone Chart
17	Quality Assurance Plan
23	Material Control Plan
25	System Safety Plan
27	Design Review Package

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15. Supplementary Notes

16. Abstract

This report summarizes analysis, design, and experimental testing done on the propellant effector (valve plus electromechanical actuator) for the ALS main engine.

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